A Cyclodextrin Diphosphane as a First and Second Coordination Sphere Cavitand: Evidence for Weak C–H···Cl–M Hydrogen Bonds within Metal-Capped Cavities

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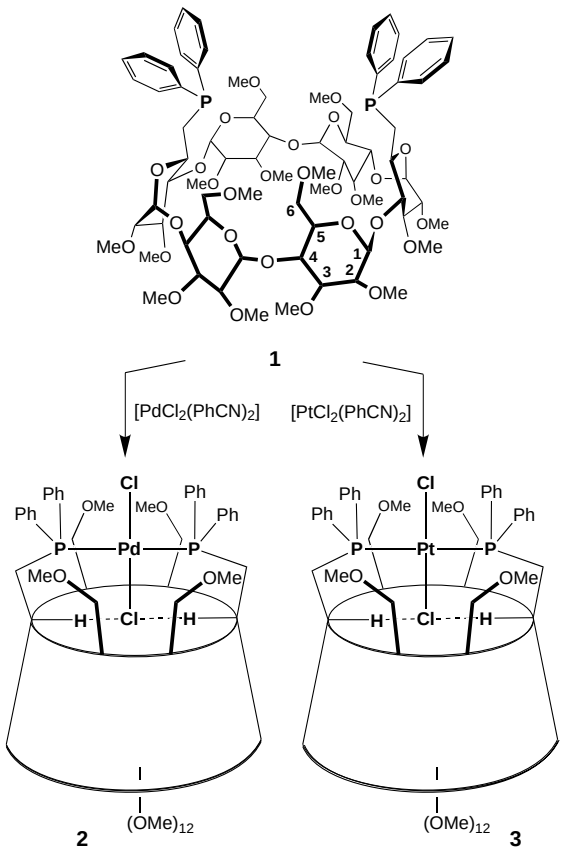
Metallocavitands are coordination compounds that provide the opportunity to study host–guest interactions between metal-bonded substrates and the internal part of a molecular cavity.[1–11] Those in which a metal center is rigidly held above the entrance of an opened cavity are particularly promising since they may force the latter to form a second coordination sphere with certain ligands.[12, 13] Through coordination, the sequestered fragments are subjected to restricted movement and their controlled positioning is expected to allow specific, weak interactions to operate.

Modified cyclodextrins are amongst the most studied molecular cavities, in particular for their ability to form inclusion complexes with a large range of substrates in water.[14–16] Many interesting applications derive from this property,[17–21] but to date little structural data are available about weak, noncovalent interactions involving the inwardly pointing CH bonds.[22] On the other hand, the systematic weak interglucose C-6-H(n)···O-5($n+1$) hydrogen bonds which contribute to the stability of the structures of methylated CDs are well documented.[23, 24] We have recently shown that chelating diphosphanes built on an α-cyclodextrin scaffold such as **1** constitute unique probes for examining substitution reactions occurring at a confined metal center.[13] In the course of our investigations on the coordination properties of such diphosphanes, we have now found that upon complexation M–Cl fragments are systematically included in the CD cavity, the chlorine atom(s) being noncovalently bonded in an unprecedented way to inner-cavity CH groups.

Cavitand **1**[13] bears two short phosphane units ideally suited for forming *trans*-chelate complexes with d^8 metals. Thus, reaction of **1** with $[PdCl_2(PhCN)_2]$ afforded complex **2** in approximately 40% yield (Scheme 1, Table 1).[25, 26] All NMR data are consistent with a twofold molecular symmetry, while the formation of a monomeric species was inferred from the FAB mass spectrum which displays a strong peak at m/z 1710 with the appropriate isotopic profile for the corresponding $[M+H]^+$ ion. The presence in the ^{13}C NMR spectrum of a virtual triplet for the PCH_2 carbon atoms ($J(PC) + {}^3J(PC) = 23$ Hz) is in keeping with *trans*-arranged phosphorus atoms.[27] The platinum analogue **3** which was obtained from $[PtCl_2(PhCN)_2]$ is characterized by a $J(PPt)$ coupling constant of 2637 Hz, typical of a *trans* configuration (Table 1). The *trans*-spanning behavior of **2** was confirmed by an X-ray diffraction study (Figure 1). The most striking feature of this structure is the presence of a Pd–Cl bond that points inside the cyclodextrin cone with the chlorine atom located near the two inner H-5 atoms of the phosphorus-substituted glucose units. A separation of 2.64(2) Å can be calculated for H-5···Cl by assuming a C-5-H-5 bond length of 0.95 Å. A clear indication of a weak CH···Cl interaction arises from the ^1H NMR spectra of both complexes (**2** and **3**), which show that two H-5 atoms have undergone a significant low-field shift of approximately 0.8 ppm(!), with respect to the free ligand.



Scheme 1. trans-Binding behavior of **1**. Synthesis of **2** and **3**.

A further illustration of the "chlorophillic" binding behavior of cyclodextrin **1** is provided by its reaction with [PdClMe(cod)] (cod = cycloocta-1,5-diene), which results in quantitative formation of **4** (Scheme 2, Table 2). Again diphosphane **1** behaves as a *trans*-binding ligand, as can easily be deduced from the presence of a triplet for the methyl group ($^3J(PH) = 6.0$ Hz) in the ^1H NMR spectrum. As for the complexes described above, the two H-5 atoms close to the phosphorus atoms are significantly low-field shifted relative to their counterparts in free **1** ($\Delta\delta = +1.35$ ppm). Furthermore, 2D ROESY spectra unambiguously confirmed the spatial proximity of the methyl group and the PPh_2 groups, hence establishing the preference of the cavity for the

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Table 1. Selected analytical data.

2: yellow powder, yield 40% after column chromatography (SiO_2, CH_2Cl_2/MeOH, 94:6, v/v). R_f (CH_2Cl_2/MeOH, 94:6, v/v) = 0.31; m.p. 185 °C (decomp); ^{1}H NMR (200 MHz, $CDCl_3$, 25 °C): δ = 2.67 (br d, $^2J_{H\text{-}6a,H\text{-}6b}$ = 10.3 Hz; H-6a^{A,D}), 2.85 (s, 6H; CH_3O-6), 3.20 (s, 6H; CH_3O-6), 3.47 (s, 6H; OCH_3), 3.49 (s, 6H; OCH_3), 3.52 (s, 6H; OCH_3), 3.61 (s, 6H; OCH_3), 3.65 (s, 6H; OCH_3), 3.78 (s, 6H; OCH_3), 3.06–4.11 (m, 32H; H-2, H-3, H-4, H-5^{B,C,E,F}, H-6a^{B,C,E,F}, H-6b), 4.78 (d, $^3J_{H\text{-}1,H\text{-}2}$ = 2.7 Hz, 2H; H-1), 5.01 (d, $^3J_{H\text{-}1,H\text{-}2}$ = 3.0 Hz, 2H; H-1), 5.13 (d, $^3J_{H\text{-}1,H\text{-}2}$ = 3.5 Hz, 2H; H-1), 5.13 (br t, ^3J = 10.1 Hz, 2H; H-5^{A,D}), 7.33–7.43 (m, 12H; H$_{meta}$ and H$_{para}$), 7.55–7.63 (m, 4H, H$_{ortho}$), 8.07–8.16 ppm (m, 4H; H$_{ortho}$); ^{13}C{^{1}H} NMR (50.3 MHz, $CDCl_3$, 25 °C): δ = 34.94 (virtual t, $^1J_{C,P} + {}^3J_{C,P'}$ = 23.0 Hz; C-6^{A,D}), 57.50, 57.73 (CH_3O-6), 58.94, 59.13 (×2) (CH_3O-2), 61.13, 61.50, 61.82 (CH_3O-3), 70.02 (C-4^{A,D}), 70.61, 70.80 (C-6^{B,C,E,F}), 71.33, 71.46 (C-5^{B,C,E,F}), 80.28, 80.64, 80.77, 81.23 (×2), 81.69, 81.75, 83.36 (C-2, C-3, C-4^{B,C,E,F}), 89.90 (virtual t, $^2J_{C,P} + {}^4J_{C,P'}$ = 11.5 Hz; C-5^{A,D}), 98.27 (×2) (C-1^{B,C,E,F}), 100.77 (C-1^{A,D}), 127.51 (virtual t, $^3J_{C,P} + {}^5J_{C,P'}$ = 11.5 Hz; C$_{meta}$), 128.07 (virtual t, $^3J_{C,P} + {}^5J_{C,P'}$ = 9.8 Hz; C$_{meta}$), 130.10 (s; C$_{para}$), 130.56 (s; C$_{para}$), 133.48 (virtual t, $^2J_{C,P} + {}^4J_{C,P'}$ = 11.5 Hz; C$_{ortho}$), 135.71 ppm (virtual t, $^2J_{C,P} + {}^4J_{C,P'}$ = 13.2 Hz; C$_{ortho}$) (the C$_{ipso}$ atoms could not be identified); ^{31}P{^{1}H} NMR (121.5 MHz, $CDCl_3$, 25 °C): δ = 11.9 ppm (s); elemental analysis (%): calcd for $C_{76}H_{110}Cl_2O_{28}P_2Pd$ (1710.95): C 53.35, H 6.48; found: C 53.36, H 6.29; MS (FAB): *m/z* (%): 1710.2 (33) $[M+H]^+$, 1675.2 (17) $[M-Cl]^+$, 1638.2 (13) $[M-2Cl]^+$.

3: pale yellow, yield: 41% after column chromatography (SiO_2, CH_2Cl_2/MeOH 94:6, v/v). R_f (CH_2Cl_2/MeOH, 94:6, v/v) = 0.31; m.p. 218 °C (decomp); ^{1}H NMR (200 MHz, $CDCl_3$, 25 °C): δ = 2.62 (d, $^2J_{H\text{-}6a,H\text{-}6b}$ = 10.7 Hz; H-6a^{A,D}), 2.88 (s, 6H; CH_3O-6), 3.19 (s, 6H; CH_3O-6), 3.46 (s, 6H; OCH_3), 3.48 (s, 6H; OCH_3), 3.52 (s, 6H; OCH_3), 3.60 (s, 6H; OCH_3), 3.64 (s, 6H; OCH_3), 3.78 (s, 6H; OCH_3), 3.05–4.08 (m, 32H; H-2, H-3, H-4, H-5^{B,C,E,F}, H-6a^{B,C,E,F},H-6b), 4.76 (d, $^3J_{H\text{-}1,H\text{-}2}$ = 2.6 Hz, 2H; H-1), 5.00 (d, $^3J_{H\text{-}1,H\text{-}2}$ = 2.9 Hz, 2H; H-1), 5.13 (d, $^3J_{H\text{-}1,H\text{-}2}$ = 3.4 Hz, 2H; H-1), 5.18 (br t, ^3J = 9.7 Hz, 2H; H-5^{A,D}), 7.32–7.44 (m, 12H; H$_{meta}$ and H$_{para}$), 7.58–7.64 (m, 4H; H$_{ortho}$), 8.09–8.16 ppm (m, 4H; H$_{ortho}$); ^{13}C{^{1}H} NMR (50.3 MHz, $CDCl_3$, 25 °C): δ = 36.55 (virtual t, $^1J_{C,P} + {}^3J_{C,P'}$ = 21.5 Hz; C-6^{A,D}), 57.53, 57.86 (CH_3O-6), 58.94, 59.20, 59.30 (CH_3O-2), 61.13, 61.50, 61.86 (CH_3O-3), 69.99 (C-4^{A,D}), 70.54, 70.84 (C-6^{B,C,E,F}), 71.39 (×2) (C-5^{B,C,E,F}), 80.28, 80.74 (×2), 81.26 (×2), 81.69 (×2), 83.39 (C-2, C-3, C-4^{B,C,E,F}), 89.10 (virtual t, $^2J_{C,P} + {}^4J_{C,P'}$ = 11.5 Hz; C-5^{A,D}), 98.21, 98.27 (C-1^{B,C,E,F}), 100.67 (C-1^{A,D}), 127.42 (virtual t, $^3J_{C,P} + {}^5J_{C,P'}$ = 9.8 Hz; C$_{meta}$), 127.97 (virtual t, $^3J_{C,P} + {}^5J_{C,P'}$ = 9.8 Hz; C$_{meta}$), 130.17 (s; C$_{para}$), 130.56 (s; C$_{para}$), 133.55 (virtual t, $^2J_{C,P} + {}^4J_{C,P'}$ = 11.5 Hz; C$_{ortho}$), 135.71 (virtual t, $^2J_{C,P} + {}^4J_{C,P'}$ = 11.5 Hz; C$_{ortho}$) (the C$_{ipso}$ atoms could not be identified); ^{31}P{^{1}H} NMR (121.5 MHz, $CDCl_3$, 25 °C): δ = 7.8 (s with Pt satellites, $^1J_{Pt,P}$ = 2637 Hz); elemental analysis (%) calcd for $C_{76}H_{110}Cl_2O_{28}P_2Pt \cdot 0.5\,C_6H_6$ (1799.61+39.06): C 51.61, H 6.19; found: C 51.64, H 6.08; MS (FAB): *m/z* (%): 1799.7 (0.1) $[M+H]^+$, 1763.8 (0.5) $[M-Cl]^+$. The molecular structure was confirmed by an X-ray analysis.

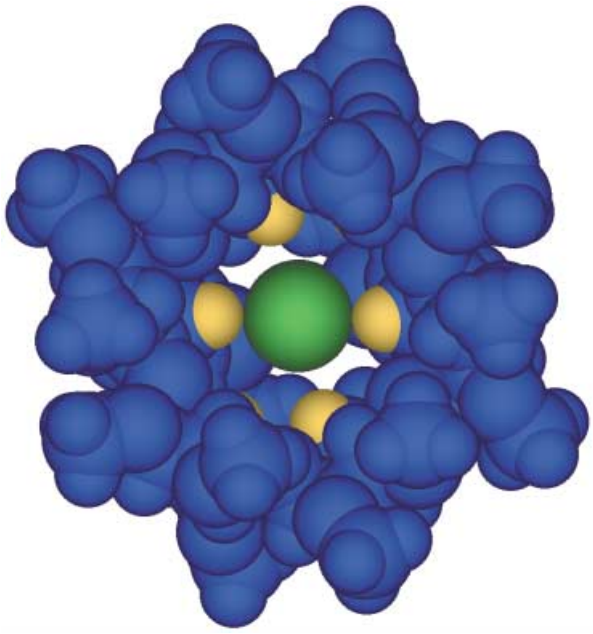
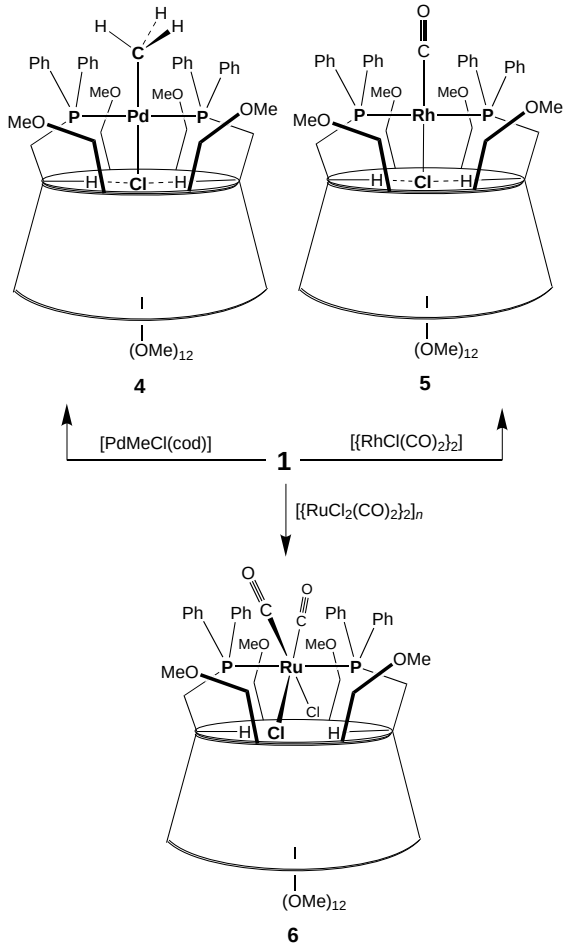


Figure 1. X-ray structure (space-filling model) of the C_2-symmetric complex **2**. View from the bottom showing the Cl(2) atom in green and the H-5 atoms in yellow (two of them are hidden). The butanone molecule included inside the CD has been omitted for clarity. Selected bond lengths [Å] and angle [°]: Pd-Cl(1) 2.2908(19), Pd-Cl(2) 2.2875(19), Pd-P 2.3619(13); P-Pd-P 171.81(7). Shortest H-5 ··· Cl(2) distances: 2.64(2) Å.



Scheme 2. Selective entrapment of M–Cl bonds inside an α-cyclodextrin cavity.

polarized Pd–Cl moiety rather than for the less-polar Pd-alkyl group. Selective inclusion of the M–Cl bond in the cavity was also observed for the rhodium complex **5** obtained by reaction of **1** with $[\{RhCl(CO)_2\}_2]$ (Table 2). The H-5 atoms in the β position to the P atoms are shifted to 0.96 ppm.

The ability of cavitand **1** to bind M–Cl fragments seems to be a general trend, even when the diphosphane is incorporated into higher coordination spheres. Thus, reaction of **1** with $[RuCl_2(CO)_2]_n$ in boiling ethoxyethanol afforded the octahedral *trans*,*cis*,*cis*-complex **6** in approximately 70% yield, together with trace amounts of another, unidentified complex (Scheme 2, Table 2).[28] The infrared spectrum of **6** displays two strong carbonyl bands, as expected for two *cis*-coordinated carbonyl groups. The ^{1}H NMR spectrum is consistent with a C_2-symmetric molecule and reveals that in this case, two pairs of H-5 atoms are involved in hydrogen bonding with the Cl atoms.[29] The stereochemistry

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Table 2. Selected analytical data.

4: yellow powder, yield: 76%; R_f (CH_2Cl_2/MeOH, 94:6, v/v) = 0.31; m.p. 178 °C (decomp); ^{1}H NMR (500 MHz, C_6D_6, 25 °C): δ = 0.02 (t, $^3J_{H,P}$ = 6.0 Hz, 3H; $PdCH_3$), 2.77 (m, 2H; H-6a^{A,D}) 3.20 (s, 6H; OCH_3), 3.22 (s, 6H; OCH_3), 3.30 (s, 6H; OCH_3), 3.31 (s, 6H; OCH_3), 3.33 (s, 6H; OCH_3), 3.39 (s, 6H; OCH_3), 3.86 (s, 6H; CH_3O-6), 3.88 (s, 6H; CH_3O-6), 3.13–4.71 (32H; H-2, H-3, H-4, H-5^{B,C,E,F}, H-6a^{B,C,E,F}, H-6b), 5.05 (d, ^3J = 2.6 Hz, 2H; H-1), 5.22 (d, ^3J = 3.1 Hz, 2H; H-1), 5.40 (d, ^3J = 3.5 Hz, 2H; H-1), 5.98 (br t, ^3J = 9.5 Hz, 2H; H-5^{A,D}), 6.86–7.25 (m, 12H; H_{meta} and H_{para}), 7.70–7.73 (m, 4H; H_{ortho}), 7.88–7.91 ppm (m, 4H; H_{ortho}); ^{13}C{^{1}H} NMR (50.3 MHz, C_6D_6, 25 °C): δ = 4.51 ($PdCH_3$), 37.30 (virtual t, $^1J_{C,P} + {}^3J_{C,P'}$ = 24.7 Hz; C-6^{A,D}), 57.00, 57.36 (CH_3O-6), 59.19, 59.56, 60.05 (CH_3O-2), 60.96, 61.39, 62.11 (CH_3O-3), 70.00 (C-4^{A,D}), 72.27, 72.34 (C-5^{B,C,E,F}), 72.41, 72.50 (C-6^{B,C,E,F}), 81.35, 81.58 (×2), 81.88, 82.30, 82.47, 82.83, 84.17 (C-2, C-3, C-4^{B,C,E,F}), 88.80 (virtual t, $^2J_{C,P} + {}^4J_{C,P'}$ = 9.9 Hz; C-5^{A,D}), 98.33, 98.43 (C-1^{B,C,E,F}), 101.09 (C-1^{A,D}), 128.00 (virtual t, $^3J_{C,P} + {}^5J_{C,P'}$ = 9.8 Hz; C_{meta}), 128.43 (virtual t, $^3J_{C,P} + {}^5J_{C,P'}$ = 9.8 Hz; C_{meta}), 129.70 (s; C_{para}), 130.39 (s; C_{para}), 131.11 (d, $^1J_{C,P} + {}^3J_{C,P'}$ = 39.6 Hz; C_{ipso}), 133.54 (virtual t, $^2J_{C,P} + {}^4J_{C,P'}$ = 11.5 Hz; C_{ortho}), 136.00 (virtual t, $^2J_{C,P} + {}^4J_{C,P'}$ = 13.2 Hz; C_{ortho}), 137.77 ppm (virtual t, $^1J_{C,P} + {}^3J_{C,P'}$ = 39.6 Hz; C_{ipso}); ^{31}P{^{1}H} NMR (121.5 MHz, $CDCl_3$, 25 °C): δ = 19.4 ppm (s); elemental analysis (%) calcd for $C_{77}H_{113}ClO_{28}P_2Pd$ (1690.53): C 54.71, H 6.74; found: C 54.48, H 6.45; MS (FAB): *m/z* (%): 1690.6 (17) $[M]^+$, 1675.5 (10) $[M-CH_3]^+$, 1653.6 (15) $[M-Cl]^+$, 1638.6 (9) $[M-CH_3-Cl]^+$.

5: orange-yellow powder, yield: 64%; R_f (CH_2Cl_2/MeOH, 94:6, v/v) = 0.30; m.p. 182 °C (decomp); IR (KBr): $\tilde{\nu}$ = 1976 cm^{-1} (C≡O); ^{1}H NMR (500 MHz, C_6D_6, 25 °C): δ (assignment by COSY) = 2.84 and 3.65 (br AB, 4H, H-6^{A,D}), 3.16 (s, 6H, OCH_3), 3.19 (d, 2H, H-2$^{B,E\ or\ C,F}$), 3.20 (d, 2H, H-2^{A,D}), 3.21 (d, 2H, H-2$^{C,F\ or\ B,E}$), 3.22 (s, 6H, OCH_3), 3.25 (s, 6H, OCH_3), 3.28 and 4.40 (AB, ^2J = 10.6 Hz, 4H, H-6$^{C,F\ or\ B,E}$), 3.32 (s, 6H, OCH_3), 3.33 (d, 2H, H-4^{A,D}), 3.39 (s, 6H, OCH_3), 3.44 (s, 6H, OCH_3), 3.61 (d, 2H, H-3$^{C,F\ or\ B,E}$), 3.65 and 4.33 (AB, ^2J = 10.6 Hz, 4H, H-6$^{B,E\ or\ C,F}$), 3.80 (s, 6H, CH_3O-6), 3.87 (s, 6H, CH_3O-6), 4.08 (t, ^3J = 8.8 Hz, 2H, H-4$^{B,E\ or\ C,F}$), 4.14 (t, ^3J = 9.1 Hz, 2H, H-3^{A,D}), 4.15 (t, ^3J = 8.8 Hz, 2H, H-4$^{C,F\ or\ B,E}$), 4.47 (br d, ^3J = 9.3 Hz, 2H, H-5$^{C,F\ or\ B,E}$), 4.55 (br d, ^3J = 9.3 Hz, 2H, H-5$^{B,E\ or\ C,F}$), 5.11 (d, $^3J_{H-1,H-2}$ = 2.6 Hz, 2H, H-1^{A,D}), 5.19 (d, $^3J_{H-1,H-2}$ = 2.9 Hz, 2H, H-1$^{B,E\ or\ C,F}$), 5.36 (d, $^3J_{H-1,H-2}$ = 3.3 Hz, 2H, H-1$^{C,F\ or\ B,E}$), 5.59 (br t, ^3J = 9.7 Hz, 2H, H-5^{A,D}), 6.95–7.25 (m, 12H, H_{meta} and H_{para}), 7.78–7.82 (m, 4H, H_{ortho}), 8.17–8.21 ppm (m, 4H, H_{ortho}); ^{13}C{^{1}H} NMR (125.8 MHz, C_6D_6, 25 °C): δ = 35.83 (virtual t, $^1J_{C,P} + {}^3J_{C,P'}$ = 22.4 Hz, C-6^{A,D}), 57.25, 57.41 (CH_3O-6), 59.14, 59.30, 59.44 (CH_3O-2), 61.25, 61.72, 62.12 (CH_3O-3), 70.78 (C-4^{A,D}), 71.95, 72.32
(C-5^{B,C,E,F}), 72.12, 72.49 (C-6^{B,C,E,F}), 81.15, 81.63, 81.70 (×2), 81.88, 81.78, 82.84, 84.12 (C-2, C-3, C-4^{B,C,E,F}), 89.23 (virtual t, $^2J_{C,P} + {}^4J_{C,P'}$ = 10.4 Hz, C-5^{A,D}), 98.31, 98.81 (C-1^{B,C,E,F}), 101.37 (C-1^{A,D}), 127.97 (virtual t, $^3J_{C,P} + {}^5J_{C,P'}$ = 9.6 Hz, C_{meta}), 128.49 (virtual t, $^3J_{C,P} + {}^5J_{C,P'}$ = 9.6 Hz, C_{meta}), 129.69 (s, C_{para}), 130.36 (s, C_{para}), 133.35 (virtual t, $^2J_{C,P} + {}^4J_{C,P'}$ = 12.0 Hz, C_{ortho}), 134.54 (virtual t, $^1J_{C,P} + {}^3J_{C,P'}$ = 44.2 Hz, C_{ipso}), 135.58 (virtual t, $^2J_{C,P} + {}^4J_{C,P'}$ = 13.6 Hz, C_{ortho}), 140.68 ppm (virtual t, $^1J_{C,P} + {}^3J_{C,P'}$ = 42.6 Hz, C_{ipso}); NMR ^{31}P{^{1}H} (121.5 MHz, C_6D_6, 25 °C): δ = 17.9 ppm (d, $^1J_{Rh,P}$ = 132 Hz); elemental analysis (%) calcd for $C_{77}H_{110}ClO_{29}P_2Rh \cdot C_6H_6$ (1700.02 + 78.11): C 56.07, H 6.58; found: C 56.20, H 6.62; MS (FAB): *m/z* (%): 1679.4 (12) $[M-Cl+O]^+$, 1670.4 (5) $[M-CO]^+$, 1663.4 (3) $[M-Cl]^+$, 1635.5 (19) $[M-CO-Cl]^+$.

6: yellow; yield: 61%. R_f (CH_2Cl_2/MeOH, 94:6, v/v) = 0.31; m.p. 145–147 °C; ^{1}H NMR (400 MHz, $CDCl_3$, 25 °C): δ (assignment by COSY) = 2.54 (m, 2H; H-6a^{A,D}), 2.83 (s, 6H; CH_3O-6), 2.95 (dd, $^3J_{H-1,H-2}$ = 2,7 Hz, $^3J_{H-2,H-3}$ = 10.0 Hz, 2H; H-2^{A,D}), 3.06 (t, $^3J_{H-3,H-4} = {}^3J_{H-4,H-5}$ = 9.2 Hz, 2H; H-4^{A,D}), 3.12 (dd, $^3J_{H-1,H-2}$ = 2,9 Hz, $^3J_{H-2,H-3}$ = 9.6 Hz, 2H; H-2$^{B,E\ or\ C,F}$), 3.15 (dd, 2H; H-6a$^{C,F\ or\ B,E}$), 3.17 (dd, 2H; H-2$^{C,F\ or\ B,E}$), 3.36 (dd, $^2J_{H-6a,H-6b}$ = 11.9 Hz, $^3J_{H-5,H-6b}$ = 1.5 Hz, 2H; H-6b$^{C,F\ or\ B,E}$), 3.39 (s, 6H; CH_3O-6), 3.43 (s, 6H; OCH_3), 3.47 (s, 6H; OCH_3), 3.50 (s, 6H; OCH_3), 3.60 (s, 6H; OCH_3), 3.65–3.75 (3 overlapping dd, 6H; H-6a$^{B,E\ or\ C,F}$, H-3^{A,D}, and H-4$^{B,E\ or\ C,F}$), 3.66 (s, 6H; OCH_3), 3.69 (s, 6H; OCH_3), 3.75–3.82 (3 overlapping dd, 6H; H-3$^{B,E\ or\ C,F}$, H-3$^{C,F\ or\ B,E}$, H-4$^{C,F\ or\ B,E}$), 3.93 (m, $^2J_{H-6b,H-6a}$ = 11.5 Hz, 2H; H-6b^{A,D}), 3.97 (dt, ^3J = 10.8 Hz, 2H; H-5$^{B,E\ or\ C,F}$), 4.36 (dt, ^3J = 9.5 Hz, 2H; H-5$^{C,F\ or\ B,E}$), 4.45 (d, ^3J = 2.7 Hz, 2H; H-1^{A,D}), 4.57 (br d, ^3J = 7.0, 2H; H-6b$^{B,E\ or\ C,F}$), 4.97 (br t, ^3J = 9.5 Hz, 2H; H-5^{A,D}), 5.06 (d, ^3J = 2.9 Hz, 2H; H-1$^{B,E\ or\ C,F}$), 5.11 (d, ^3J = 3.1 Hz, 2H; H-1$^{C,F\ or\ B,E}$), 7.30–7.40 (m, 12H; H_{meta} and H_{para}), 7.48–7.53 (m, 4H; H_{ortho}), 7.89–7.95 ppm (m, 4H; H_{ortho}); ^{13}C{^{1}H} NMR (50.3 MHz, $CDCl_3$, 25 °C): δ = 33.50 (virtual t, $^1J_{C,P} + {}^3J_{C,P'}$ = 28.0 Hz; C-6^{A,D}), 57.10, 58.15 (CH_3O-6), 58.61, 58.84, 59.07 (CH_3O-2), 61.20, 61.27, 61.43 (CH_3O-3), 70.58 (C-4^{A,D}), 71.03, 71.17 (C-6^{B,C,E,F}), 70.67, 71.39 (C-5^{B,C,E,F}), 78.93, 79.95, 80.80 (×2), 81.69, 81.98, 82.83, 83.72 (C-2, C-3, C-4^{B,C,E,F}), 92.21 (virtual t, $^2J_{C,P} + {}^4J_{C,P'}$ = 9.9 Hz; C-5^{A,D}), 97.26, 99.32, 102.21 (C-1), 127.94 (virtual t, $^3J_{C,P} + {}^5J_{C,P'}$ = 11.5 Hz; C_{meta}), 128.30 (virtual t, $^3J_{C,P} + {}^5J_{C,P'}$ = 8.2 Hz; C_{meta}), 129.74 (s; C_{para}), 130.43 (s; C_{para}), 131.35 (virtual t, $^2J_{C,P} + {}^4J_{C,P'}$ = 9.8 Hz; C_{ortho}), 132.79 (virtual t, $^1J_{C,P} + {}^3J_{C,P'}$ = 42.8 Hz; C_{ipso}), 134.76 (virtual t, $^2J_{C,P} + {}^4J_{C,P'}$ = 11.5 Hz; C_{ortho}) 139.94 (virtual t, $^1J_{C,P} + {}^3J_{C,P'}$ = 46.2 Hz; C_{ipso}), 193.66 ppm (t, $^2J_{C,P}$ = 12 Hz; CO); ^{31}P{^{1}H} NMR (121.5 MHz, $CDCl_3$, 25 °C): δ = 12.4 (s); elemental analysis (%) calcd for $C_{78}H_{110}O_{30}P_2Cl_2Ru \cdot 0.5\,CH_2Cl_2$ (1761.62+42.47): C 52.26, H 6.20; found: C 52.18, H 6.43; MS (FAB): *m/z* (%): 1763.4 (8) $[M+H]^+$, 1735.4 (30) $[M-CO+H]^+$, 1706.4 (20) $[M-2CO]^+$, 1699.4 (35) $[M-Cl-CO)]^+$.

of the complex and the presence of both M–Cl bonds inside the cavity was confirmed by an X-ray study (Figure 2). The solid-state structure exhibits some disorder that is characterized by two possible orientations of the "$Ru(CO)_2Cl_2$" cross which rotates by approximately 37° about the P–P axis on switching from one rotamer to the other (isomer ratio 80:20). In other words, the chlorine atoms compete for the central position inside the cyclodextrin. Both rotamers deviate somewhat from ideal C_2 symmetry. In the major one (Figure 2) the Cl(2) atom is close to four consecutive H-5 atoms (H···Cl separation ranging from 2.75(2) to 3.00(2) Å), while Cl(1) interacts with the two remaining H-5 atoms (2.84(2) and 2.88(2) Å). Clearly the weakness of the individual Cl···H-5 interactions favors easy reorientation of the M–Cl bonds within the upper part of the cavity. A general survey on the occurrence of CH···Cl hydrogen bonds in molecular structures indicates that such interactions take place only with

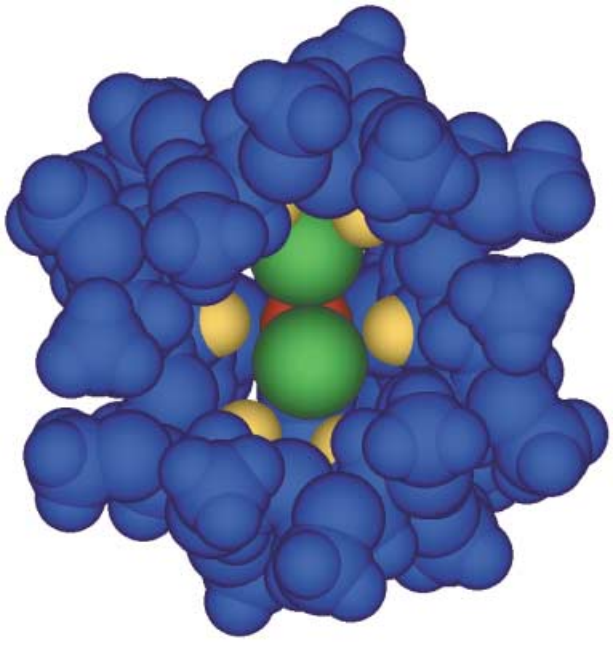

Figure 2. Molecular structure of **6** (major isomer). View from the bottom showing the chlorine atoms in green (Cl(1) down, Cl(2) up), the H-5 atoms in yellow, and the ruthenium atom in red. The included benzene molecule has been omitted for clarity. Selected bond lengths [Å]: Ru-P 2.423(2) and 2.425(2), Ru-Cl(1) 2.408(3), Ru-Cl(2) 2.355(3); shortest Cl(1)···H-5 distances: 2.75(2), 2.80(2), 2.84(2), 3.00(2); shortest Cl(2)···H-5 distances: 2.84(2) and 2.88(2).

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Cl atoms having a marked anionic character.[30] This feature is also realized, but to a lesser extent, in the M–Cl bonds of complexes **2**–**6**.

The present study illustrates for the first time the ability of an α-cyclodextrin cavity to recognize a transition metal M–Cl bond through weak Cl···H-5 interactions in the solid state as well as in solution. The fact that such subtle interactions could be observed in non-aqueous media is a consequence of the absence of stronger competing supramolecular forces, such as the hydrophobic effect, which usually plays a prevailing role in the formation of CD inclusion complexes. Overall these results illustrate the potential of modified cyclodextrins as second-sphere ligands.

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[25] Some insoluble material, presumably of oligomeric nature, was also formed during this synthesis. However, this is not the case for complexes **4**–**6** which were obtained from starting complexes containing very good leaving groups.

[26] Crystal structure analysis of $\mathbf{2}\cdot C_4H_8O$: crystals suitable for X-ray diffraction were obtained by slow diffusion of pentane into a butanone solution of the complex. Crystal data: $M_r = 1782.98$, hexagonal, space group $P6_522$, $a = b = 14.8846(3)$, $c = 67.0615(15)$ Å, $V = 12867.0(5)$ Å^3, $Z = 6$, $\rho_{calcd} = 1.381$ g cm^{-3}, $Mo_{K\alpha}$ radiation ($\lambda = 0.71073$ Å), $\mu = 0.395$ mm^{-1}. Data were collected on a Bruker SMART 1000 CCD system at 133(2) K. The structure was solved by direct methods and refined on F_o^2 by full-matrix least squares (program SHELXL-97, G. M. Sheldrick, University of Göttingen). All non-hydrogen atoms were refined anisotropically; hydrogen atoms were included using a riding model. The absolute configuration (and thus the enantiomeric space group assignment) was determined by a Flack x parameter of $-0.07(3)$. Refinement proceeded to $wR2 = 0.1025$ for all 5529 reflections and $R1 = 0.0413$ for data with $I > 2\sigma(I)$. The compound crystallizes with a butanone molecule positioned inside the cyclodextrin cavity. CCDC-181579 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/conts/retrieving.html (or from the Cambridge Crystallographic Data Centre, 12, Union Road, Cambridge CB2 1EZ, UK; fax: (+44) 1223-336-033; or deposit@ccdc.cam.ac.uk).

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[28] Crystal structure analysis of $\mathbf{6}\cdot C_6H_6$: crystals suitable for X-ray diffraction were obtained by slow diffusion of pentane into a benzene solution of the complex; $M_r = 1839.68$, orthorhombic, space group $P2_12_12_1$, $a = 15.353(2)$, $b = 24.313(2)$, $c = 26.952(3)$ Å, $V = 10060.9(19)$ Å^3, $Z = 4$, $\rho_{calcd} = 1.211$ g cm^{-3}, $Mo_{K\alpha}$ radiation ($\lambda = 0.71073$ Å), $\mu = 0.311$ mm^{-1}. Data were collected on a Kappa CCD Enraf Nonius system at 173(2) K. The structure was solved by direct methods and refined on F_o^2 by full-matrix least squares (program SHELXL-97, G. M. Sheldrick, University of Göttingen). All non-hydrogen atoms were refined anisotropically; hydrogens were included using a riding model. The absolute structure was determined by refining Flack's x parameter ($x = -0.01(4)$). $R1 = 0.0830$ and $\omega R2 = 0.2096$ for 12112 data with $I > 2\sigma(I)$. The compound crystallizes with a benzene molecule included inside the cyclodextrin cavity. CCDC-181578 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/conts/retrieving.html (or from the Cambridge Crystallographic Data Centre, 12, Union Road, Cambridge CB2 1EZ, UK; fax: (+44) 1223-336-033; or deposit@ccdc.cam.ac.uk).

[29] The behavior of the CD cavity towards the "$RuCl_2(CO)_2$" unit strongly contrasts with that of a recently reported *p-tert*-butylcalix[4]-arene-derived diphosphane. Upon complexation, the latter favors inclusion of a "Ru–CO" rod over that of a "Ru–Cl" fragment; see reference [6].

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A Stepwise Huisgen Cycloaddition Process: Copper(I)-Catalyzed Regioselective "Ligation" of Azides and Terminal Alkynes**

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Huisgen 1,3-dipolar cycloadditions[1] are exergonic fusion processes that unite two unsaturated reactants and provide fast access to an enormous variety of five-membered hetero-

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