Molecular Recognition of Titanium(IV) Alkoxides by 2,6-Bis(hydroxymethyl)-*p*-cresol in the Crystal Engineering of Hybrid Organic−Inorganic Networks

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The design of hybrid organic−inorganic networks requires a fine understanding of the interactions that control molecular recognition and self-assembly processes between inorganic and organic chemical species. Here we report our study on the reaction between titanium(IV) alkoxides, known to be tetrameric $[Ti_4(OR)_{16}]$ (**1**) in the solid state,[1] and an aromatic ligand such as 2,6-bis(hydroxymethyl)-*p*-cresol (BHMPC **2**). The choice of titanium(IV) alkoxides was motivated by their widespread use as precursors in both conventional (paints, inks, plastics, cosmetics, ceramics...) and high-tech (coatings, membranes, photoanodes, capacitors...) materials. From a previous study, it was known that bridging positions were more reactive toward hydrolysis or complexation than terminal ones and that tripodal ligands were able to remove selectively all bridging OR groups.[2] As shown in Figure 1, starting from the same planar tetrameric structure, a perfect geometrical match between octahedral edges of (**1**) and hydroxo moieties of (**2**) could be anticipated.

Upon reaction of the ligand (**2**) with $Ti(OEt)_4$, a new complex for which the tetrameric structure of (**1**) was preserved but with all edges occupied by sic molecules of (**2**) was obtained (cf. Figure 2).[3] The inorganic core of this tetranuclear complex (**3**) is composed of two μ_3-oxo groups bridging the four titanium atoms. The tetranuclear titanium core is surrounded by six ligands (**2**) acting by groups of two, either as chelating, chelating−bridging, or tridentate units.[4] As the bond valence sum around atom O3 is 1.28 against 2.05 for O2, we assume that the chelating ligand (**2**) involves a CH_2OH moiety.

The persistence of (**3**) in solution was checked by ^1H and ^{13}C NMR in $CDCl_3$.[5] (**3**) has an interesting shape which may be described as an analogue of a doubly fused calix[3]arene. Due to the presence of two divergent cavities, (**3**) may act as receptor for solvent molecules Figure 3).

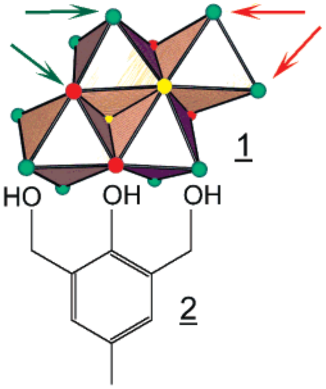

Figure 1. Molecular recognition between octahedral edges of a $[Ti_4(OR)_{16}]$ tetramer (**1**) and 2,6-bis(hydroxymethyl)-*p*-cresol (**2**) molecules.

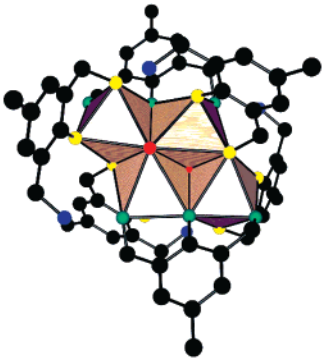

Figure 2. Molecular structure of $[Ti_4(\mu_3\text{-}O)_2\{Ph(\mu_2\text{-}O)(CH_2OH)_2\}_2\{Ph(\mu_2\text{-}O)(CH_2O)(CH_2OH)\}_2\{Ph(O(CH_2OH)_2\}_2]$ (**3**) showing the two μ_2-oxo groups (red), the free $-CH_2OH$ moieties (blue) and the bidentate (yellow oxygen atoms) or tridentate (green oxygen atoms) coordination mode of (**2**).

Figure 3. Divergent association of the six phenyl rings around the inorganic Ti_4O_2 core forming a doubly fused-calix[3].

Indeed, in the X-ray crystal structure of (**3**), one dioxan molecule and one ethanol molecule are found to be trapped within each cavity. These filled double-calix type molecules form in the crystalline state a 1D-network through π-stacking of aromatic groups (Figure 4). To better characterize the crystal engineering of such inclusion networks, we assume, in the spirit of the Hohenberg−Kohn theorem,[6] that the total molecular energy E can always be partitioned between a purely electrostatic contribution EB and a purely electronic functional $F[\rho]$ which takes care of all the exchange and electronic correlations: $E_{tot} = EB + F[\rho]$. Now, for the same molecular fragment placed into two different chemical environments (in a vacuum on one hand and inside a crystalline lattice on the other hand for example), we may safely

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(1) Wright, D. A.; Williams, D. A. *Acta Crystallogr.* **1968**, *B24*, 1107.

(2) Schildknecht-Weymann, S.; Henry, M. *Chem. Commun.* Manuscript submitted.

(3) Orange prismatic crystals suitable for X-ray diffraction were deposited overnight from a clear red-orange solution obtained by injecting 15 mL of a solution of (**2**) (0.67 g, 4 mmol) in 1,4-dioxane into 5 mL of a solution of titanium ethoxide (0.45 g, 2 mmol) in ethanol under vigorous stirring. UV-vis: $\lambda_{max} = 343$ nm ($\epsilon = 19\,400$ $cm^{-1}\cdot mol^{-1}\cdot L$), $\lambda_{max} = 234$ nm ($\epsilon = 45\,000$ $cm^{-1}\cdot mol^{-1}\cdot L$). IR (KBr pellet): 3440 (s), 2962 (m), 2910 (m), 2853 (m), 1636 (m), 1473 (s), 1256 (s), 1219 (m), 1160 (M), 1119 (m), 1078 (m), 1046 (m), 998 (m), 871 (m), 840 (s), 673 (m), 579 (s) cm^{-1}.

(4) Crystallographic data: crystal dimensions 0.14 × 0.11 × 0.09 mm^3, formula $Ti_4O_{26}C_{66}H_{88}$, FW 1487.0, triclinic, space group *P*-1, $a = 11.1076(9)$ Å, $b = 11.871(2)$ Å, $c = 11.655(2)$ Å, $\alpha = 80.769(5)°$, $\beta = 70.036(5)°$, $\gamma = 77.303(5)°$, $V = 1764.1(5)$ Å^3, $Z = 1$, R(wR) = 0.082(0.104) for 3131 reflections with $|F_0| \geq 3.0\sigma(|F_0|)$. μ_3-oxo: Ti1−O1 = 1.953(2) Å, Ti2−O1 = 1.948(6) Å, Ti2−O1 = 2.011(7) Å with Ti−O−Ti bond angles = 100.4(2)−108.0(2)°. Chelating: Ti1−O2 = 1.843(7) Å (phenolic), Ti1−O3 = 2.084(7) Å (alcoholic). Chelating-bridging: Ti2−O7 = 1.867(9) Å (phenolic) and Ti1−O5 = 1.967(6) Å, Ti2−O5 = 2.004(8) Å (alcoholic). Tridentate: Ti2−O10 = 2.048(9) Å, Ti1−O10 = 2.085(7) Å (phenolic) and Ti1−O8 = 1.808(7) Å, Ti2−O9 = 1.857(9) Å (alcoholic).

(5) ^1H NMR: δ 2.16(6H, $C\mathbf{H}_3$), 2.20(6H, $C\mathbf{H}_3$), 2.22 ppm (6H, $C\mathbf{H}_3$), 4.0−6.0 (24H, CH_2), 6.70 (2H, Ph**H**), 6.79(4H, Ph**H**), 6.84(2H, Ph**H**), 6.92(2H, Ph**H**), 6.95(2H, Ph**H**) ppm. ^{13}C NMR: Tridentate δ 20.5 ($\mathbf{C}H_3$), 73.5 (2 × $\mathbf{C}H_2O$), 125.2−128.0 (5 × $\mathbf{C}_{Ph}$), 152.1 ppm ($O\mathbf{C}_{Ph}$). Bridging−chelating: δ 20.2 ($\mathbf{C}H_3$), 74.1, 74.7 ($\mathbf{C}H_2O$), 128.7−131.6 (5 × $\mathbf{C}_{Ph}$), 157.4 ppm ($O\mathbf{C}_{Ph}$). Chelating δ 20.2 ($\mathbf{C}H_3$), 60.6, 62.2 ($\mathbf{C}H_2O$), 128.1−128.8 (5 × $\mathbf{C}_{Ph}$), 158.6 ppm ($O\mathbf{C}_{Ph}$).

(6) Hohenberg, P.; Kohn, W. *Phys. Rev. B* **1964**, *136*, 864.

10.1021/ja0156136 CCC: $20.00

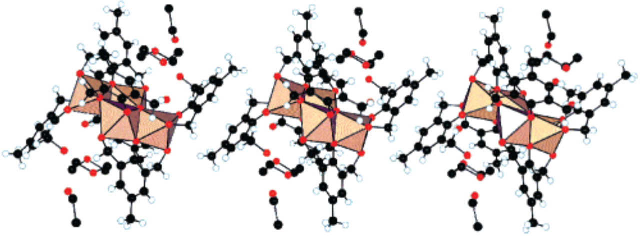

Figure 4. 1D molecular network based on compound (**3**) filled with dioxane and ethanol inside the two divergent cavities.

Table 1. Electrostatic Balances (EB) Computed from the Partial Charge Model[7] for the Two Inclusion Networks Based on **3** (A) with Included 1,4-dioxan (B) and Co-solvent Molecules (S)

fragment	EB/kJ·mol^{-1} (S = EtOH)	EB/kJ·mol^{-1} (S = $CHCl_3$)[11]
network	−14110.4	−13923.1
$A \supset 2(B + S)$	−14069.9	−13778.8
$A \supset 2B$	−13997.8	−13692.5
$A \supset 2S$	−13871.6	−13582.6
A (free)	−13794.8	−13479.4
B (free)	−88.6	−82.0
S (free)	−25.7	−8.4

assume that $F_1[\rho] \sim F_2[\rho]$. Thus a direct probing of molecular interactions E_{int} through the difference in the EB values: $E_{\text{int}} \sim \text{EB}(1) - \text{EB}(2)$ appears as possible. As, the computation of such EB values from a given charge distribution is straightforward, we may explore, with a rigorous and quantitative energetic criterion, a variety of networks. To compute a reliable charge distribution, we have used the partial charge model,[7] which requires only the input of molecular or crystalline structures, once an electronegativity and an atomic radii scales have been selected. In the present case we have used configuration energy of elements[8] and ab initio atomic orbital radii[9] to approximate electronegativity values and chemical hardnesses, respectively.

The left part of Table 1 gives the results obtained for the ethanol solvate. For instance, the π-stacking energy is directly given by $\Delta E_1 = \text{EB}(N) - \text{EB}[A \supset 2(B + S)] = -40.4$ kJ·mol^{-1} (here $\supset$ means included), if we assume that interchain interactions are negligible. The energy associated with the inclusion of the two dioxan molecules in the two divergent cavities may be evaluated as: $\Delta E_2 = \text{EB}[A \supset 2B] - \text{EB}[A_{\text{free}}] - 2(\text{EB}[B_{\text{free}}]) = -25.8$ kJ·mol^{-1}, that is about -13 kJ·mol^{-1} per molecule. Similar evaluation leads for the inclusion of ethanol to $\Delta E_3 = \text{EB}[A \supset 2S] - \text{EB}[A_{\text{free}}] - 2(\text{EB}[S_{\text{free}}]) = -25.4$ kJ·mol^{-1}, that is again -13 kJ·mol^{-1} per molecule. Dioxan is thus approximately as tightly bonded as ethanol. Finally, the interaction energy between dioxan and ethanol within a cavity is evaluated as: $\Delta E_4 = \text{EB}[A \supset 2(B + S)] - \text{EB}[A \supset 2B] - 2(\text{EB}[S_{\text{free}}]) = -20.7$ kJ·mol^{-1} or as $\Delta E_4 = \text{EB}[A \supset 2(B + S)] - \text{EB}[A \supset 2S] - 2(\text{EB}[B_{\text{free}}]) = -21.1$ kJ·mol^{-1}, that is -10.5 kJ·mol^{-1} for one interaction. All of these values are typical of van der Waals interactions (energy less than 5*kT*). It is worth noting that all of these values were computed on a crystal structure with no hydrogen atom on 1,4-dioxan or ethanol fragments. A careful analysis of O···O distances reveals that rather strong intramolecular hydrogen bonds should exist between O3 and O6 (252 pm) and between O4 and O9 (278 pm). As no intermolecular hydrogen bonds were detected, our energy values should not be significantly modified by including the missing hydrogen atoms.

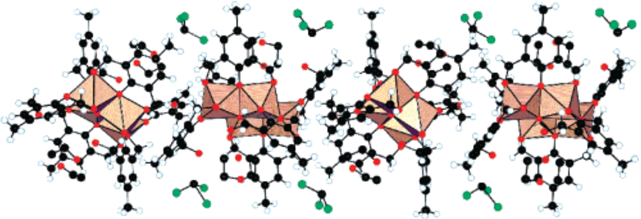

Figure 5. 1D molecular network based on compound (**3**) filled with dioxan and chloroform inside the two divergent cavities.

To check the strength of dioxan inclusion inside the cavities, the tetranuclear complex (**3**) was recrystallized from chloroform.[10] Crystal structure analysis showed that dioxan molecules indeed remained trapped in the cavities while EtOH replaces were replaced by $CHCl_3$. However, two types of inclusion complexes were present in the unit cell. The first one contained $CHCl_3$, forming a hydrogen bond with the neighboring dioxan ($d_{O24\cdots C61} = 308.4$ pm). The second one contained $CHCl_3$, forming a hydrogen bond with the free CH_2OH arm of the chelating BHMPC ligand ($d_{O2\cdots C59} = 300.9$ pm). These two complexes are further associated into a 1D-network through interactions between methyl groups of one complex with the phenyl rings of the other one (Figure 5). A third $CHCl_3$ molecule is accommodated between these chains. Table 1 (right) compares the averaged EB values of the naked fragments with the EB value of the complete network.

For this new network, the overall packing energy is found to be much lower ($\Delta E_1 = -144.3$ kJ·mol^{-1}) owing to the presence of a $CHCl_3$ molecule between the chains. The binding energies are found to be in this case -25 kJ·mol^{-1} and -43 kJ·mol^{-1} for dioxan and $CHCl_3$, respectively. The interaction between dioxan and $CHCl_3$ within the cavity is estimated as -16.1 kJ·mol^{-1}, a slightly lower value than that between dioxan and EtOH. These results shows that changing the solvent has a rather complex effect as both the geometry and the interactions energies are deeply modified. Consequently, this work is a first step toward a better characterization of the role played by the solvent in crystal engineering. Work is currently under progress on several other molecular networks to check if a quantitative modelization of all the molecular interactions encountered in crystal engineering can be reached.

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Supporting Information Available: Tables of crystal data, structure solution and refinement, atomic coordinates, bond lengths and angles, and anisotropic thermal parameters in CIF format. Tables of computed partial charges, frontier indexes, retrosynthetic indexes used to build Table 1 (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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(7) Henry, M. *Coord. Chem. Revs* **1998**, *178−180*, 1109.

(8) (a) Mann, J. B.; Meek, T. L.; Allen, L. C. *J. Am. Chem. Soc.* **2000**, *122*, 2780. (b) Mann, J. B.; Meek, T. L.; Knight, E. T.; Capitani, J. F.; Allen, L. C. *J. Am. Chem. Soc.* **2000**, *122*, 5132.

(9) Waber, J. T.; Cromer, D. T.; *J. Chem. Phys.* **1965**, *42*, 4116.

(10) Crystallographic data: red-orange crystal dimensions 0.18 × 0.10 × 0.08 mm^3, formula $Ti_8O_{49}C_{131}H_{162}Cl_{18}$, FW 3542.1, triclinic, space group *P*-1, $a = 12.8922(4)$ Å, $b = 14.1422(4)$ Å, $c = 22.8758(4)$ Å, $\alpha = 81.271(6)°$, $\beta = 77.401(6)°$, $\gamma = 81.550(6)°$, $V = 3995.1(1)$ Å^3, $Z = 1$, R(wR) = 0.099-(0.122) for 10414 reflections with $|F_0| \geq 3.0\sigma(|F_0|)$.

(11) Fractional atoms O25 and C66 have been discarded for the computation.