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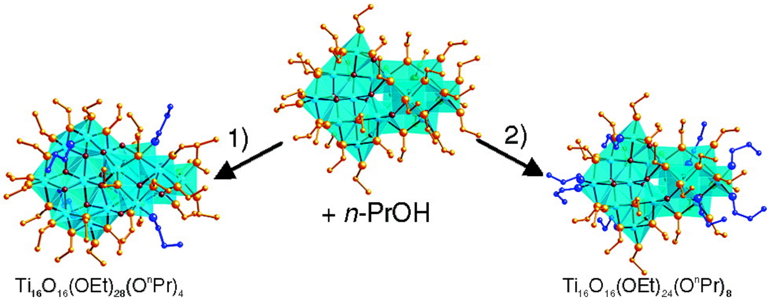

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Reactivity of Titanium Oxo Ethoxo Cluster [$Ti_{16}O_{16}(OEt)_{32}$]. Versatile Precursor of Nanobuilding Block-Based Hybrid Materials

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Abstract: Oxo alcoxo metallic clusters can be employed as inorganic nanobuilding blocks to obtain well-defined organic−inorganic hybrid materials. A better understanding of the surface reactivity of the clusters should allow optimization of the elaboration of hybrid materials through a better control of the hybrid interface. The oxo alcoxo cluster $Ti_{16}O_{16}(OEt)_{32}$ presents a shell of labile ethoxy groups that can be selectively transalcoholyzed with preservation of the titanium oxo core, leading to new oxo alcoxo clusters $Ti_{16}O_{16}(OEt)_{32-x}(OR)_x$ (R: alkyl, phenyl, styrenic, etc. groups). The reactivity of the $Ti_{16}O_{16}(OEt)_{32}$ cluster toward aliphatic and aromatic alcohols is investigated to determine both the kinetics and the number of substituted titanium atoms, which are strongly dependent on the nature of the alcohol. Characterization of the organic modification of the cluster is performed in situ by liquid ^{13}C NMR measurements, using the molecular structures of two new clusters, $Ti_{16}O_{16}(OEt)_{28}(O^nPr)_4$ and $Ti_{16}O_{16}(OEt)_{24}(O^nPr)_8$ (O^nPr = propoxy groups), as references. The structures of these clusters have been established using single-crystal X-ray diffraction. Moreover, a complete spectroscopic assignment of each ethoxy group is proposed after combining crystallographic data, ^{13}C NMR T_1 relaxation measurements, and $^1H-^1H$, $^1H-^{13}C$ 2D NMR experiments. Finally, the cluster is functionalized with polymerizable ligands via transalcoholysis and transesterification reactions using hydroxystyrene and acetoxystyrene.

Introduction

When properly functionalized, perfectly defined inorganic nanobuilding blocks, such as metal oxo alkoxo clusters, can be assembled without damage into various types of structures to create new hybrid materials.[1] Hybrid organic−inorganic materials, composed of organic and inorganic components combined over length scales ranging from a few angstroms to a few tens of nanometers, are nanocomposites that offer great potential for high value-added applications.[2] Numerous hybrid organic−inorganic materials have been developed, mainly by taking advantage of the mild chemical conditions of the sol−gel process.[3] Sol−gel chemistry allows nanoscale combination of inorganic and organic, or even bioactive, components into a single hybrid composite, providing access to an immense new area of materials science. The development of these multifunctional advanced materials has a major impact on future applications in fields such as optics, electronics, ionics, mechanics, membranes, protective coatings, catalysis, sensors, and biology. Characteristics of existing hybrid materials include tunable mechanical properties between those of glasses and those of

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(1) (a) Sanchez, C.; Soler-Illia, G. J. A. A.; Ribot, F.; Lalot, T.; Mayer C.; Cabuil, V. *Chem. Mater*. **2001**, *13*, 3061−3083. (b) Ribot, F.; Sanchez, C. *Comments Inorg. Chem*. **1999**, *20*, 327−371. (c) Schubert, U. *Chem. Mater*. **2001**, *13*, 3487−3494. (d) Kickelbick, G.; Schubert, U. *Monatsh. Chem.* **2001**, *132*, 13−30.

(2) (a) Wilkes, G. L.; Orler, B.; Huang H. H. *Polym. Prepr*. **1985**, *26*, 300−301. (b) Sur, G. S.; Mark, J. E. *Eur. Polym. J*. **1985**, *21*, 1051−1052. (c) Morikawa, A.; Iyoku, Y.; Kakimoto, M.; Imai, Y. *J. Mater. Chem*. **1992**, *2*, 679−689. (d) Chujo, Y.; Saegusa, T. *Adv. Polym. Sci.* **1992**, *100*, 11. (e) Novak, B. M. *Adv. Mater*. **1993**, *5*, 422−433. (f) Loy, D. A.; Shea, K. J. *Chem. Rev*. **1995**, *95*, 1431−1442. (g) Corriu, R. J. P.; Leclercq, D. *Angew. Chem., Int. Ed*. **1996**, *35*, 1420−1436. (h) Schubert, U.; Hüsing, N.; Lorenz, A. *Chem. Mater*. **1995**, *7*, 2010−2027. (i) Sanchez, C.; Ribot, F. *New J. Chem.* **1994**, *18*, 1007−1047.

(3) (a) Brinker, C. J.; Scherrer, G. W. *Sol−gel Science: The Physics and Chemistry of Sol−gel Processing*; Academic Press: San Diego, CA, 1990. (b) Livage, J.; Henry, M.; Sanchez, C. *Prog. Solid State Chem.* **1988**, *18*, 259−341.

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polymers, improved optical properties, and improved catalytic or membrane-based properties. More precisely, existing hybrid materials with excellent laser efficiencies and good photostability, very fast photochromic response, very high and stable second-order nonlinear optical response, or original pH sensors and electroluminescent diodes have been reported.[4]

Despite these successes, the sol−gel process generally yields amorphous materials that exhibit some polydispersity in the size and composition of the components of the hybrids. The nanostructure, the degree of organization, and the relative properties of such materials certainly depend on the chemical nature of their components, but they also rely on the synergy between them. Thus, a key point for the design of new hybrids is tuning the nature, the extent, and the accessibility of the inner interfaces.

A suitable method to reach a better definition of the inorganic component is based on self-assembly to achieve a deeper control of the materials, in terms of the local and semi-local structure (i.e., the degree of organization). The ability to create “organized matter” at the micro- and nanoscales has been a significant breakthrough due to the discovery that micellar and lyotropic liquid-crystal phases can act as templates for periodic hybrid organic−inorganic materials.[5] One of the most striking examples is the synthesis of mesostructured hybrid networks. The combination of self-assembly and sol−gel chemistry has led to materials with excellently controlled porosity (pore size, morphology, and arrangement) and has allowed the preparation of films, powders, monoliths, or spheres.[5]

An alternative approach to achieve better control of the inorganic phase is to elaborate hybrids by assembling well-defined nanobuilding blocks (NBBs).[1] NBBs are defined as perfectly calibrated preformed objects that maintain their integrity in the final material. NBBs can be clusters,[1] organically pre- or post-functionalized nanoparticles,[6] nano-core−shells, or layered compounds able to intercalate organic components. The literature reports a large number of metal oxo clusters based on silicon, tin, or transition-metal chemistries that are potential nanobuilding blocks for hybrid materials. Such species are usually prepared in solution through the controlled substoichiometric hydrolysis of the metallic alkoxides $M(OR)_n$ or the corresponding complexed alkoxides, $M(OR)_{n-x}(LZ)_x$, (where LZ is a complexing ligand). These clusters are isolated from the ill-defined oxo polymers concurrently formed by crystallization, frequently resulting in low yields. These species, characterized by single-crystal X-ray diffraction, present perfectly defined structures in which the metallic centers usually exhibit coordination numbers larger than their valence states. The stability of these clusters increases with their nuclearity and is enhanced by the presence of complexing organic ligands that chelate or bridge the metallic centers.[7]

The high ionicity of the M−C bond, when M is a transition metal, makes it very sensitive to hydrolysis or nucleophilic attacks. Therefore, the route of functionalizing transition-metal-based nanobricks with M−C bonds cannot be used. Different strategies have been described in the literature to overcome this problem, including functionalization by complexing groups or the formation of stable M−O−Si−R bonds. The functionalization of metal oxide nanoclusters can be realized by grafting organic groups on preformed oxometalate cores or by in situ functionalization of the clusters during their formation. Functional groups on the organic shell of the inorganic cluster allow the formation of covalent bonds with an organic polymer to give an NBB-based hybrid material.

We focus our work on the cluster $Ti_{16}O_{16}(OEt)_{32}$. The *Ti16* comprises a metallic $Ti_{16}O_{16}$ oxo core surrounded by a shell of 32 ethoxides.[8] *Ti16* is stable in solution (toluene and ethanol), and the ethoxy groups present at the surface are labile, with the ability to be selectively exchanged by *n*-propanol without destruction of the oxo core.[9] Only eight ethoxy groups are exchanged through transalcoholysis even in the presence of an excess of *n*-propanol. From chemical analysis and NMR data, the presence of a cluster with a general formula $Ti_{16}O_{16}(OEt)_{24}(O^nPr)_8$ as the main product has been reported;[9] however, its structure has not yet been determined. The integrity of the metallic oxo core is usually verified by ^{17}O NMR (after the enrichment of the cluster by $H_2{}^{17}O$ during its synthesis), while the organic alcoxy groups are characterized by ^1H and ^{13}C NMR.[9,10]

The stability of this high nuclearity cluster toward nucleophilic species can thus be used to establish connections between clusters. Moreover, the reactivity of these titanium oxo clusters toward alcohol molecules can be advantageously used with the aim of designing nanostructured hybrid materials. Indeed, hybrid nanocomposites made of *Ti16* and dendrimers or amphiphilic block copolymers have been recently reported.[11]

However, when transition-metal oxo clusters are used as NBBs, better knowledge of the number of accessible functionalities, their exact location correlated with their spectroscopic assignment, and the control of the kinetic parameters allow tuned substitutions and are of paramount importance for the development of tailor-made NBB-based hybrid materials. Moreover, a better understanding of the reactivity of the organic shell of the cluster allows controlled modification and better tuning of the affinities and compatibility between substituants and poly-

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(4) (a) Gomez-Romero, P.; Sanchez, C. *Functional Hybrid Material*; Wiley VCH: Weinheim, Germany, 2004. (b) Sanchez, C.; Lebeau, B. *MRS Bull.* **2001**, 377−387. (c) Sanchez, C.; Lebeau, B.; Chaput, F.; Boilot, J. P. *Adv. Mater.* **2003**, *15*, 1969−1994.

(5) (a) Soler-Illia, G. J. A. A.; Sanchez, C.; Lebeau, B.; Patarin, J. *Chem. Rev.* **2002**, *102*, 4093. (b) *Biomimétisme et Matériaux*; Série Arago 25; OFTA: Paris, 2001. (c) Bensaude-Vincent, B.; Arribart, H.; Bouligand, Y.; Sanchez, C. *New J. Chem.* **2002**, *26*, 1−5. (d) Sanchez, C.; Soler-Illia, G. J. A. A.; Ribot, F.; Grosso, D. *C. R. Acad Sci.* **2003**, *6*, 1131−1151. (e) Soler-Illia, G. J. A. A.; Crepaldi, E. L.; Grosso, D.; Sanchez, C. *Curr. Opin. Colloid Interface Sci.* **2003**, *8*, 109−126.

(6) (a) Scolan, E.; Sanchez, C. *Chem. Mater*. **1998**, *10*, 3217−3323. (b) Roux, S.; Soler-Illia, G. J. A. A.; Demoustier-Champagne, S.; Audebert, P.; Sanchez, C. *Adv. Mater*. **2003**, *15*, 217−221.

(7) (a) Steunou, N.; Robert, F.; Boubekeur, K.; Ribot, F.; Sanchez, C. *Inorg. Chim. Acta* **1998**, *279*, 144−151. (b) Toledano, P.; In, M.; Sanchez, C. *C. R. Acad. Sci., Ser. II* **1991**, *313*, 1247−1253. (c) Boyle, T. J.; Alam, T. M.; Tafoya, C. J. *Inorg. Chem*. **1998**, *37*, 5588−5594. (d) Gautier-Luneau, I.; Mosset, A.; Galy, J. *Z. Kristallogr.* **1987**, *180*, 83−95. (e) Doeuff, S.; Dromzee, Y.; Taulelle, F.; Sanchez, C. *Inorg. Chem*. **1989**, *28*, 4439−4445.

(8) (a) Mosset, A.; Galy, J. *C. R. Acad. Sci., Ser I.* **1988**, *307*, 1747−1750. (b) Schmid, R.; Mosset, A.; Galy, J. *J. Chem. Soc., Dalton Trans.* **1991**, 1999−2005.

(9) Chen, Y. W.; Klemperer, W. G.; Park, C. W. *Mater. Res. Soc. Symp. Proc*. **1992**, *271*, 57−63.

(10) (a) Day, V. W.; Eberspacher, T. A.; Klemperer, W. G.; Park, C. W.; Rosenberg, F. S. *J. Am. Chem. Soc*. **1991**, *113*, 8190−8192. (b) Scolan, E.; Magnenet, C.; Massiot, D.; Sanchez, C. *J. Mater. Chem*. **1999**, *9*, 2467−2474. (c) Le Calvé, S.; Alonso, B.; Rozes, L.; Sanchez, C.; Rager, M. N.; Massiot, D. *C. R. Chim.* **2004**, *7*, 241−248.

(11) (a) Soler-Illia, G. J. A. A.; Rozes, L.; Boggiano, M. K.; Sanchez, C.; Turrin, C. O.; Caminade, A. M.; Majoral, J. P. *Angew. Chem., Int. Ed*. **2000**, *39*, 4250−4254. (b) Soler-Illia, G. J. A. A.; Scolan, E.; Louis, A.; Albouy, P. A.; Sanchez, C. *New J. Chem*. **2001**, *25*, 156−165. (c) Steunou, N.; Forster, S.; Florian, P.; Sanchez, C.; Antonietti, M. *J. Mater. Chem.* **2002**, *12*, 3426−3430.

meric dispersion media, therefore increasing the homogeneity of the resulting hybrid material.

Concerning the modification of the *Ti₁₆* cluster, little has been reported since the works of Klemperer et al.[9] and Soler et al.[11a,b] Therefore, in the present article we report a careful investigation of the behavior of the *Ti_{16}* cluster in the presence of both aliphatic alcohols (methanol, *n*-propanol, *n*-butanol, *i*-propanol, and 4-cyclohexyl-1-butanol) and aromatic alcohols (benzyl alcohol and phenol).

The present study presents for the first time:

(i) Complete knowledge of the reactivity of specific "nano bricks" toward different alcohols, with NMR investigation of the number and location of substituted titanium sites.

(ii) The molecular structures of the cluster $Ti_{16}O_{16}(OEt)_{24}(O^nPr)_8$ and of the intermediate, $Ti_{16}O_{16}(OEt)_{28}(O^nPr)_4$, resolved by single-crystal X-ray diffraction.

(iii) The kinetics of the ethoxide group substitutions with different alcohols followed by NMR analysis (^1H and ^{13}C).

(iv) The structural and spectroscopic data on two perfectly defined propoxy modified *Ti_{16}* clusters, combined with *T_1* relaxation and 2D NMR experiments, ROESY, which allow a complete spectroscopic assignment of the surface-capping ethoxide groups of the $Ti_{16}O_{16}(OEt)_{32}$ cluster.

To elaborate hybrid materials by copolymerization of a functional cluster with an organic monomer, new *Ti_{16}* clusters carrying polymerizable groups have been synthesized. The grafting of polymerizable ligands such as hydroxystyrene or acetoxystyrene, as reported in this article, could lead to new hybrid nanocomposites in which nano inorganic fillers (modified *Ti_{16}*) are covalently linked to the host organic matrix.

The results reported in this article represent an important breakthrough in metal oxo cluster chemistry. The $Ti_{16}O_{16}(OEt)_{32}$ nanobuilding unit can now be substituted in a controlled fashion by 4, 8, and 16 functional groups.

Experimental Section

Materials. Tetraethoxy orthotitanate $Ti(OEt)_4$ was purchased from Fluka. Methyl alcohol anhydrous 99.8%, 4-cyclohexyl-1-butanol 99%, benzyl alcohol anhydrous 99.8%, phenol 99+%, and 4-acetoxystyrene 96% were used as received from Aldrich. 4-Hydroxystyrene was obtained by deprotection of 4-acetoxystyrene in aqueous base conditions. Solvent (toluene and acetonitrile) and alcohols (*n*-propanol, *n*-butanol, and *i*-propanol) were dried over activated molecular sieves.

NMR Spectroscopy. ^1H, ^{13}C NMR, and ^{17}O spectra were recorded on a Bruker Avance 400 MHz spectrometer equipped with a 5-mm QNP probe head (^1H and ^{13}C) or a 10-mm broadband probe head (^{13}C and ^{17}O). Samples were made of 100 mg of $Ti_{16}O_{16}(OEt)_{32}$ dissolved in 0.6 mL of perdeuterated benzene. They were analyzed at 22 °C for the spectral characterization (COSY, ROESY, HMQC) and at 50 °C for kinetic experiments. In these experiments, alcohols (methanol, *n*-propanol, *n*-butanol, *i*-propanol, and phenol) were added at a fixed stoichiometric ratio (64 mol:32 mol of ethoxy groups).

X-ray Crystal Structure Determination. $Ti_{16}O_{16}(OEt)_{28}(O^nPr)_4$. A single crystal of the air- and moisture-sensitive compound was rapidly selected, mounted onto a glass fiber, and transferred into a cold nitrogen gas stream. Diffraction data were collected on a Nonius KappaCCD diffractometer at 123 K. Unit cell parameter determination, data collection strategy, and integration were carried out with the Nonius EVAL-14 suite of programs.[12] The data were corrected from absorption by a multiscan method.[13] The structure was solved by direct methods with SHELXS-86,[14] refined by a full least squares on F^2 and completed with SHELXL-97.[15] To avoid too large thermal displacements for some Et and Pr groups, a disorder scheme was introduced for each chain and was partially resolved by means of bond and/or angle restraints. The disorder of toluene molecules was taken care of through rigid body refinements. All non-H atoms were refined with anisotropic displacement parameters, while H atoms were simply introduced at calculated positions (riding model).

Table 1. Crystallographic Data for $Ti_{16}O_{16}(OEt)_{28}(O^nPr)_4$ and $Ti_{16}O_{16}(OEt)_{24}(O^nPr)_8$

	$Ti_{16}O_{16}(OEt)_{28}(O^nPr)_4 \cdot 2C_7H_8$	$Ti_{16}O_{16}(OEt)_{24}(O^nPr)_8 \cdot 2C_7H_8$
formula	$C_{82}H_{178}O_{48}Ti_{16}$	$C_{86}H_{192}O_{48}Ti_{16}$
M	2704.69	2760.5
temp/K	123(2)	150
crystal system	orthorhombic	orthorhombic
space group	*Pbca*	*Pbca*
a/Å	29.260(5)	29.765(10)
b/Å	20.671(5)	21.014(16)
c/Å	40.344(8)	40.20(2)
V/Å^3	24401(9)	25142(25)
Z	8	8
d_{calcd}/g·cm^{-3}	1.472	1.458
μ/mm^{-1}	1.062	1.032
λ(M$_0$ K,L$_{2,3}$)/Å	0.71073	0.71069
Θ_{max}/deg	27.50	27.52
reflns collected	201 998	171 821
independent reflns (all data)	27 714	28 605
independent reflns ($I > 2\sigma(I)$)	10 777	17 229
R_{int}(obsd/all)	0.0577/0.062	0.048/0.059
parameters	1405	1251
$R(F)$, w$R(F^2)$ ($I > 2\sigma(I)$)^a	0.0656/0.1042	0.0684/0.1584
$R(F)$, w$R(F^2)$ (all data)^a	0.1223/0.1114	0.1268/0.1749
GOF in F^2	0.98	1.61

[a] $(F) = \Sigma||F_o| - |F_c||/\Sigma|F_o|$, $wR(F^2) = [\Sigma w(|F_o|^2 - |F_c|^2)^2/\Sigma w(|F_o|^4)]^{1/2}$.

$Ti_{16}O_{16}(OEt)_{24}(O^nPr)_8$. Single crystals with a small amount of solution were swiftly transferred to paratone-N oil, selected, mounted onto a glass fiber, and cryocooled in a chilled nitrogen gas stream. Diffraction data were then collected, using a combination of ω and 2θ scans, on a Nonius KappaCCD diffractometer at 150 K. Unit cell parameter determination, data collection strategy, and integration were carried out with the Eval-14 program.[12] SADABS software[16] was used for the absorption correction, SHELXS[17] for the space group and structure determination (direct methods), and JANA2000[18] for refinements, structure completion, and structure reporting. To avoid too large thermal displacements for some Et and Pr groups, a disorder scheme was introduced for each chain and was partially resolved by means of bond and/or angle restraints. The disorder of toluene molecules was taken care of through rigid body refinements. H atoms were introduced at calculated positions only for nondisordered CH_2 groups. The final refinement with anisotropic displacement parameters for all atoms except disordered CH_2 and CH_3 C atoms (refined isotropic value) and H atoms (common, refined isotropic value) led to a residual *R* value of 0.048 (observed data) as listed in Table 1.

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(12) Duisenberg, A. J. M.; Kroon-Batenburg, L. M. J.; Schreurs, A. M. M. *J. Appl. Crystallogr.* **2003**, *36*, 220−229.

(13) Blessing, R. H. *Acta Crystallogr.* **1995**, *A51*, 33−38.

(14) Sheldrick, G. M. *SHELXS-86*: Computer program for structure solution; University of Göttingen: Göttingen, Germany, 1986.

(15) Sheldrick, G. M. *SHELXL-97*: Computer program for structure refinement; University of Göttingen: Göttingen, Germany, 1997.

(16) Sheldrick, G. M. *SADABS*: A software for empirical absorption correction; University of Göttingen: Göttingen, Germany, 1997.

(17) Sheldrick, G. M. *SHELXTL*, version 5; Siemens Analytical X-ray Instruments, Inc.: Madison, WI, 1998.

(18) Petricek, V.; Dusek, M. *JANA2000*: A crystallographic computing system; Academy of Sciences of the Czech Republic: Prague, 2000.

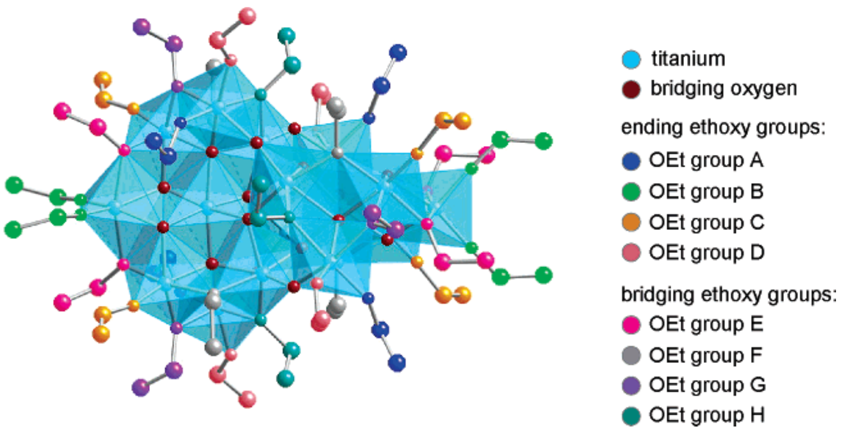

Figure 1. Representation of $\mathrm{Ti_{16}O_{16}(OEt)_{32}}$ in molecular form.

Synthesis of $\mathbf{Ti_{16}O_{16}(OEt)_{32}}$. A mixture of 7 mL of $\mathrm{Ti(OEt)_4}$ dissolved in 7 mL of anhydrous ethanol and 300 μL of neutral water was placed in a steel autoclave at 100 °C for 2 weeks. Crystals were isolated from the solution after slow cooling (1 °C/h) and were dried and stored in an inert atmosphere.

^{13}C NMR ($\mathrm{C_6D_6}$, δ ppm): 73.3, 72.8, 72.0, 71.8, 71.1, 70.8, 69.6, 69.0 (32 $\mathrm{O}C\mathrm{H_2CH_3}$); 19.8, 19.7 (two peaks separated by 0.04 ppm), 19.5, 19.0, 18.9, 18.4 (32 $\mathrm{OCH_2}C\mathrm{H_3}$).

^{17}O NMR ($\mathrm{C_6D_6}$, δ ppm): 750 (4 μ_2O); 563, 555 (8 μ_3O); 383 (4 μ_4O).

Exchange with Aliphatic Alcohols. A quantity of 0.40 mmol of $\mathrm{Ti_{16}O_{16}(OEt)_{32}}$ was dissolved in 10 mL of toluene to which an excess (25.6 mmol) of alcohol (methanol, *n*-propanol, *n*-butanol, and *i*-propanol) was added. This mixture was then placed at 50 °C for 3 days (one night for methanol). The final product was recovered, as a white solid, after vacuum distillation of all volatiles.

Colorless crystals of propanol-substituted clusters were isolated from the crude solution after 1 week at −20 °C.

$\mathbf{Ti_{16}O_{16}(OEt)_{24}(OMe)_8}$. ^{13}C NMR ($\mathrm{C_6D_6}$, δ ppm): 73.2, 72.5, 72.0, 71.0, 69.0, 68.8 (24 $\mathrm{O}C\mathrm{H_2CH_3}$); 65.5, 63.6 (8 $\mathrm{O}C\mathrm{H_3}$); 19.9, 19.8, 19.7, 19.0, 18.8, 18.1 (24 $\mathrm{OCH_2}C\mathrm{H_3}$).

$\mathbf{Ti_{16}O_{16}(OEt)_{28}(O^{\mathit{n}}Pr)_4}$. ^{13}C NMR ($\mathrm{C_6D_6}$, δ ppm): 79.5 (4 $\mathrm{O}C\mathrm{H_2CH_2CH_3}$); 73.0, 72.0, 71.6, 71.3, 70.7, 69.7, 69.0 (28 $\mathrm{O}C\mathrm{H_2CH_3}$); 27.1 (4 $\mathrm{OCH_2}C\mathrm{H_2CH_3}$); 19.8, 19.7, 19.5, 19.4, 18.9, 18.8, 18.4 (28 $\mathrm{OCH_2}C\mathrm{H_3}$); 10.3 (4 $\mathrm{OCH_2CH_2}C\mathrm{H_3}$).

$\mathbf{Ti_{16}O_{16}(OEt)_{24}(O^{\mathit{n}}Pr)_8}$. ^{13}C NMR ($\mathrm{C_6D_6}$, δ ppm): 79.3, 77.8 (8 $\mathrm{O}C\mathrm{H_2CH_2CH_3}$); 73.3, 72.0, 71.5, 70.8, 69.6, 69.1 (24 $\mathrm{O}C\mathrm{H_2CH_3}$); 27.2, 27.1 (8 $\mathrm{OCH_2}C\mathrm{H_2CH_3}$); 19.9, 19.8, 19.7, 19.1, 18.9, 18.3 (24 $\mathrm{OCH_2}C\mathrm{H_3}$); 10.9, 10.5 (8 $\mathrm{OCH_2CH_2}C\mathrm{H_3}$).

^{17}O NMR ($\mathrm{C_6D_6}$, δ ppm): 750 (4 μ_2O) 560, 553 (8 μ_3O), 382 (4 μ_4O).

$\mathbf{Ti_{16}O_{16}(OEt)_{24}(O^{\mathit{n}}Bu)_8}$. ^{13}C NMR ($\mathrm{C_6D_6}$, δ ppm): 77.8, 75.9 (8 $\mathrm{O}C\mathrm{H_2CH_2CH_2CH_3}$); 73.3, 72.1, 71.5, 70.8, 69.6, 69.1 (24 $\mathrm{O}C\mathrm{H_2CH_3}$); 36.6, 36.3 (8 $\mathrm{OCH_2}C\mathrm{H_2CH_2CH_3}$); 19.9, 19.8 (8 $\mathrm{OCH_2CH_2}C\mathrm{H_2CH_3}$); 20.0, 19.8, 19.7, 19.1, 19.0, 18.4 (24 $\mathrm{OCH_2}C\mathrm{H_3}$); 14.9, 14.5 (8 $\mathrm{OCH_2CH_2CH_2}C\mathrm{H_3}$).

Exchange with Other Alcohols. A quantity of 0.40 mmol of $\mathrm{Ti_{16}O_{16}(OEt)_{32}}$ was dissolved in 10 mL of toluene to which an excess (25.6 mmol) of alcohol (benzylic alcohol and 4-cyclohexyl-1-butanol) was added. This mixture was placed at 50 °C for 3 days. The final product was recovered, as a white solid, after vacuum distillation of all volatiles and washings with acetonitrile.

$\mathbf{Ti_{16}O_{16}(OEt)_{24}(OCH_2Ph)_8}$. ^{13}C NMR ($\mathrm{C_6D_6}$, δ ppm): 145.1, 143.2 (8 C_{ar}); 128.5, 128.4, 127.2, 126.8, 126.7, 125.3 (40 C_{ar}); 77.8, 77.4 (8 $\mathrm{O}C\mathrm{H_2Ph}$); 73.6, 72.9, 72.2, 71.2, 70.1, 70.0 (24 $\mathrm{O}C\mathrm{H_2CH_3}$); 19.9, 19.6, 19.4, 19.0, 18.8, 18.2 (24 $\mathrm{OCH_2}C\mathrm{H_3}$).

$\mathbf{Ti_{16}O_{16}(OEt)_{24}(O^{\mathit{n}}Bu^{\mathit{c}}C_6H_{11})_8}$. ^{13}C NMR ($\mathrm{C_6D_6}$, δ ppm): 78.1, 76.2 (8 $\mathrm{O}C\mathrm{H_2CH_2CH_2CH_2{}^{\mathit{c}}C_6H_{11}}$); 73.3, 72.0, 71.4, 70.8, 69.6, 69.1 (24 $\mathrm{O}C\mathrm{H_2CH_3}$); 38.5, 38.4, 34.0, 27.0, 26.9 (40 ${}^{c}C\mathrm{_6H_{11}}$); 38.3, 38.2 (8 $\mathrm{OCH_2CH_2CH_2}C\mathrm{H_2{}^{\mathit{c}}C_6H_{11}}$); 34.9, 34.6 (8 $\mathrm{OCH_2}C\mathrm{H_2CH_2CH_2{}^{\mathit{c}}C_6H_{11}}$); 23.9, 23.7 (8 $\mathrm{OCH_2CH_2}C\mathrm{H_2CH_2{}^{\mathit{c}}CH_{11}}$); 20.0, 19.8, 19.7, 19.1, 19.0, 18.4 (24 $\mathrm{OCH_2}C\mathrm{H_3}$).

Exchange with Phenol and Polymerizable Ligands. A quantity of 0.40 mmol of $\mathrm{Ti_{16}O_{16}(OEt)_{32}}$ was dissolved in 10 mL of toluene with excess of phenol. This mixture was placed at 50 °C for 3 days. The final product was recovered, as an orange powder, after vacuum distillation of all volatiles and subsequent washing with acetonitrile.

$\mathbf{Ti_{16}O_{16}(OEt)_{28}(OPh)_4}$. ^{13}C NMR ($\mathrm{C_6D_6}$, δ ppm): 167.7, 128.9, 121.9, 119.9 (24 C_{ar}); 74.4, 72.5, 72.4, 72.2, 71.3, 71.0, 70.0 (28 $\mathrm{O}C\mathrm{H_2CH_3}$); 19.8, 19.5, 18.9, 18.8, 18.6, 18.5, 18.3 (28 $\mathrm{OCH_2}C\mathrm{H_3}$).

^{17}O NMR ($\mathrm{C_6D_6}$, δ ppm): 754 (4 μ_2O); 561, 558 (8 μ_3O); 383 (4 μ_4O).

$\mathbf{Ti_{16}O_{16}(OEt)_{24}(OPh)_8}$. ^{13}C NMR ($\mathrm{C_6D_6}$, δ ppm): 167.3, 165.9, 129.4, 129.0, 121.2, 120.6, 120.2, 120.1 (48 C_{ar}); 74.2, 74.1, 73.3, 72.0, 71.2, 70.7 (24 $\mathrm{O}C\mathrm{H_2CH_3}$); 19.9, 19.1, 19.0, 18.6, 18.4, 18.3 (24 $\mathrm{OCH_2}C\mathrm{H_3}$).

^{17}O NMR ($\mathrm{C_6D_6}$, δ ppm): 755 (4 μ_2O); 559 (8 μ_3O); 383 (4 μ_4O).

$\mathbf{Ti_{16}O_{16}(OEt)_{28}(OPhCH{=}CH_2)_4}$. ^{13}C NMR ($\mathrm{C_6D_6}$, δ ppm): 168.0, 129.7, 127.1, 121.9 (24 C_{ar}); 138.2 (4 $\mathrm{OPh}C\mathrm{H{=}CH_2}$); 109.6 (4 $\mathrm{OPhCH{=}}C\mathrm{H_2}$); 74.3, 72.6, 72.4, 71.3, 71.2, 70.0 (28 $\mathrm{O}C\mathrm{H_2CH_3}$); 19.9, 19.3, 18.9, 18.8, 18.7, 18.5, 18.3 (28 $\mathrm{OCH_2}C\mathrm{H_3}$).

Results and Discussion

1. Structure of $\mathbf{Ti_{16}O_{16}(OEt)_{32}}$, *Ti₁₆*. The structure of *Ti_{16}* (Figure 1) consists of two orthogonal blocks of eight $\mathrm{TiO_6}$ octahedra with an organic shell constituted by 32 ethoxy groups.[8] The 16 titanium atoms of the inorganic core are interconnected through three different types of oxygen bridges. Four oxygen atoms are doubly bridging (μ_2O), eight are triply bridging (μ_3O), and four are quadruply bridging (μ_4O). The oxo core of *Ti_{16}* has been analyzed by ^{17}O NMR; the chemical shifts are in agreement with the structure of the cluster, as four resonances are observed that can be assigned to the three different types of oxide oxygen atoms in the structure (at 750 ppm for the μ_2O, 563 and 555 ppm for the μ_3O, and 383 ppm for the μ_4O).[9]

There are two kinds of ethoxy groups: 16 ethoxides are bonded to one titanium atom (μ_2O: terminal ethoxy groups) and the other 16 ethoxides are linked to two titanium atoms (μ_3O: bridging ethoxy groups). The geometry of the structure presents a 2 axis and a pseudo -4 axis, so that the 32 organic groups can be divided into 8 groups of 4 pseudo-equivalent ethoxy groups, named with different letters: A, B, C, and D for the terminal ethoxides and E, F, G, and H for the bridging groups.

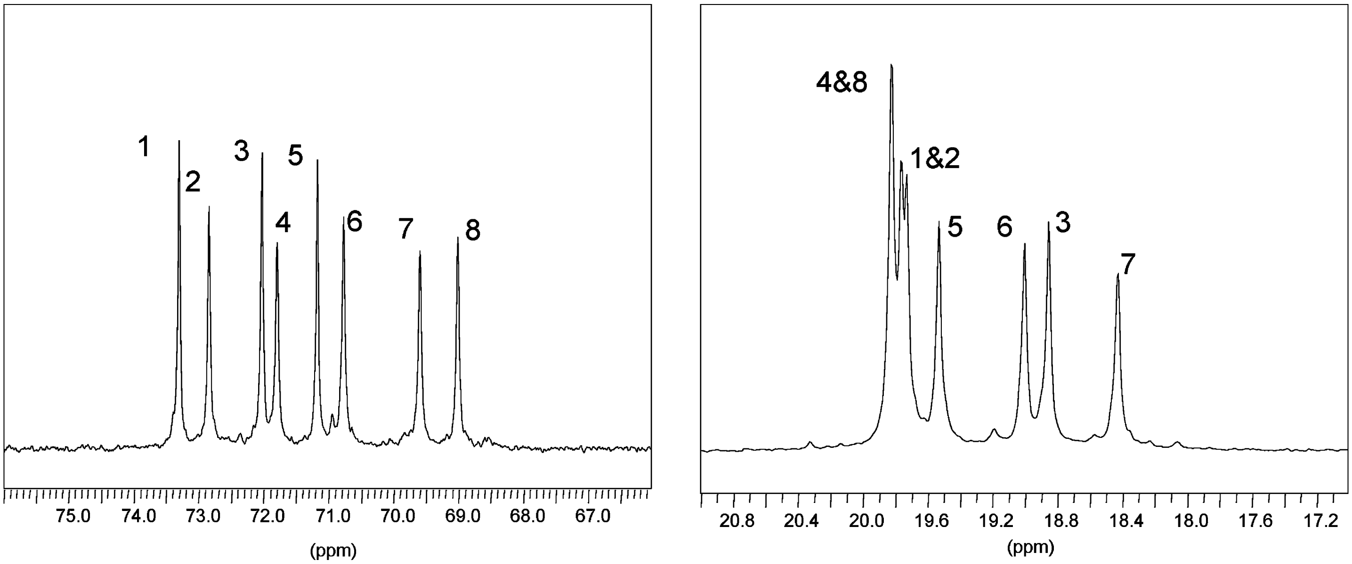

Figure 2. Extracts of $Ti_{16}O_{16}(OEt)_{32}$ liquid-state ^{13}C NMR spectrum with, on the left, the methylene region and, on the right, the methyl region.

The NMR spectra are in correlation with the structure of the cluster. In the liquid state, the pseudo-equivalent ethoxy groups become equivalent due to the Brownian motion. The ^{13}C spectrum, measured in a benzene solution, effectively presents only eight resonances in the methylene region (noted 1−8, from 69.0 to 73.3 ppm) and seven in the methyl region (from 18.4 to 19.8 ppm) with two of them being overlapped (Figure 2). Some complementary 2D NMR (COSY and HMQC) experiments enabled us to determine the correlation between methylene and methyl signals.[10c] The ^{1}H NMR spectrum is more complex: it shows eight triplets in the methyl region, but in the methylene area the signals (doublets of quadruplets) are overlapped due to the magnetic inequivalence of methylene geminal protons.[10c]

2. Reactivity of Ti_{16}. 2.1. Exchange with Aliphatic Alcohols. The reactivity of Ti_{16} toward *n*-propanol has already been reported.[9] Nevertheless, we reproduced these results to ascertain more information about the shell modification of the cluster. The transalcoholysis reaction is conducted by treating a toluene solution of the titanium cluster with a large excess (minimum 64 mol of alcohol to 32 mol of capping ethoxy groups) of *n*-propanol at 50 °C for 3 days. This cluster exhibits a peculiar behavior. Indeed, even in the presence of a very large excess (640 mol of alcohol to 32 mol of ethoxy groups) of the nonparent alcohol (*n*-propanol), only eight ethoxy groups are exchanged by propoxy groups, leading to the formation of a $Ti_{16}O_{16}(OEt)_{24}(O^{n}Pr)_{8}$ cluster; on the contrary, an equimolar treatment (32 mol of alcohol to 32 mol of alkoxy groups) does not lead to the eight-substituted cluster. The positions of the eight sites, which undergo transalcoholysis reactions, are specifically localized on the structure. This behavior has been investigated by NMR measurements in correlation with the crystallographic measurements on single crystals. The kinetics of the substitution were monitored by NMR liquid-state spectroscopy on a solution of Ti_{16} (in perdeuterated benzene) treated with a large excess of *n*-propanol (64 mol to 32 mol of ethoxy groups) at 50 °C. NMR ^{13}C spectra (Figure 3) showed the differences of reactivity of the eight groups of pseudo-equivalent ethoxides toward *n*-propanol.[10c]

At first, signal 2 decreased with the simultaneous appearance of a more deshielded signal 2′, corresponding to the incorporation of the propoxy group. A splitting in two components of peak 5 was observed and is probably due to the loss of symmetry of the cluster. After 1 h, a partially substituted $Ti_{16}O_{16}(OEt)_{28}(O^{n}Pr)_{4}$ cluster could be recovered. This chemical species is symmetric and exhibits a typical signature in ^{13}C NMR, with eight signals in the CH_2 region: seven corresponding to the residual ethoxy groups and one more deshielded at 79.5 ppm assigned to the propoxy groups. The crystallographic structure permitted assignment of the signal 2 observed by ^{13}C NMR to the alkoxy groups named A on the structure (Figure 4a).

The transalcoholysis reaction then proceeded with the simultaneous decrease of the signal 5 and the emergence of a new deshielded signal 5′ accompanied by the splitting in two of peaks 4 and 7 due to a partial substitution that produces a loss of symmetry. After 2 days, the exchange reaction with *n*-propanol leads to the modified $Ti_{16}O_{16}(OEt)_{24}(O^{n}Pr)_{8}$ cluster. The ^{13}C spectrum shows eight resonances in the methylene region. Two of these are more deshielded and can be assigned to the eight propoxy groups (two groups of four pseudo-equivalent propoxides), and the remaining six peaks correspond to the 24 residual ethoxy groups. The crystallographic study confirmed the selectivity of the exchange reaction, showing that the propoxy groups entered well-defined positions labeled A and B (Figure 4b).

The preservation of the oxo core was confirmed in the solid state by crystallographic analysis and in the liquid state by ^{17}O NMR of $Ti_{16}O_{16}(OEt)_{24}(O^{n}Pr)_{8}$ (experiments recorded on the ^{17}O enriched Ti_{16}). The ^{17}O NMR spectrum of the enriched cluster shows four signals, at 750, 560, 553, and 382 ppm, that correspond to the three types of oxygen bridges usually observed on the ^{17}O spectrum of the nonmodified cluster.[10]

The isolation and structural characterization of $Ti_{16}O_{16}(OEt)_{24}(O^{n}Pr)_{8}$ and of the intermediate product $Ti_{16}O_{16}(OEt)_{28}(O^{n}Pr)_{4}$ via single-crystal XRD allows, for the first time, a demonstration of the selectivity of transalcoholysis reactions. The transalcoholysis on Ti_{16} is sequential, and substitution takes place preferentially on the terminal groups and not on the bridging groups. On the other hand, the substitution ratio is limited to eight (versus 32 ethoxides). This selectivity is probably due to

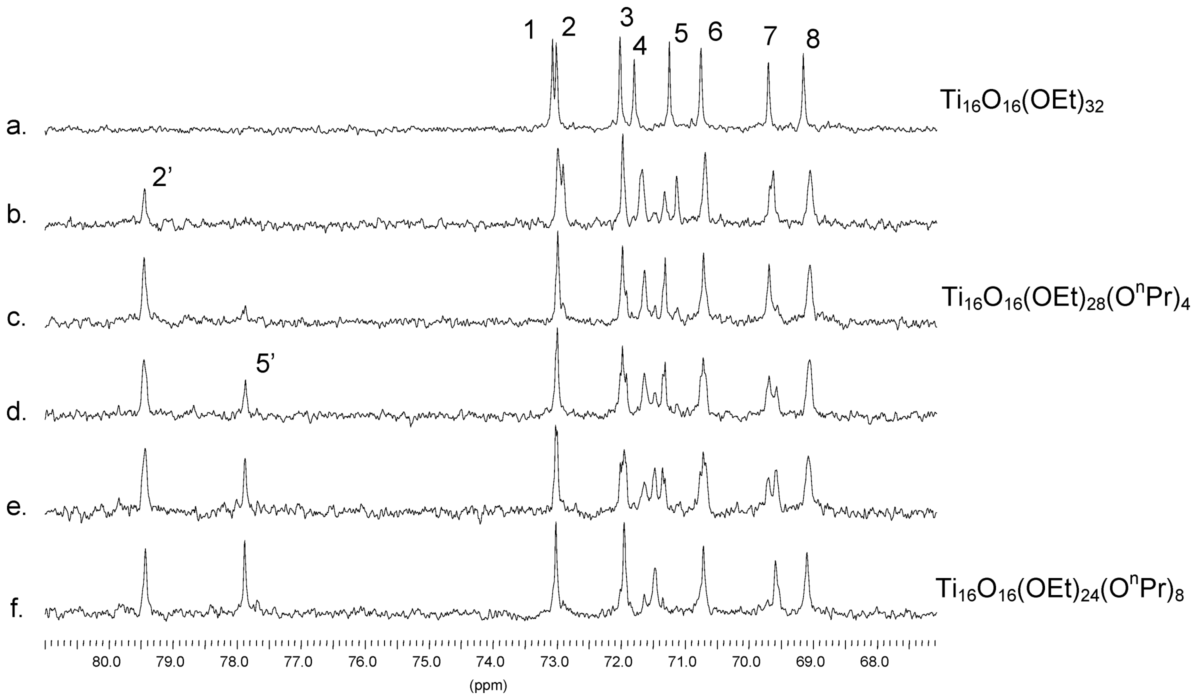

Figure 3. Kinetics of transalcoholysis reaction with *n*-propanol. Methylene region of ^{13}C spectra at 50 °C at different times after introduction of alcohol: (a) before introduction of *n*-propanol, (b) 5, (c) 55, (d) 130, (e) 270, and (f) 1800 min.

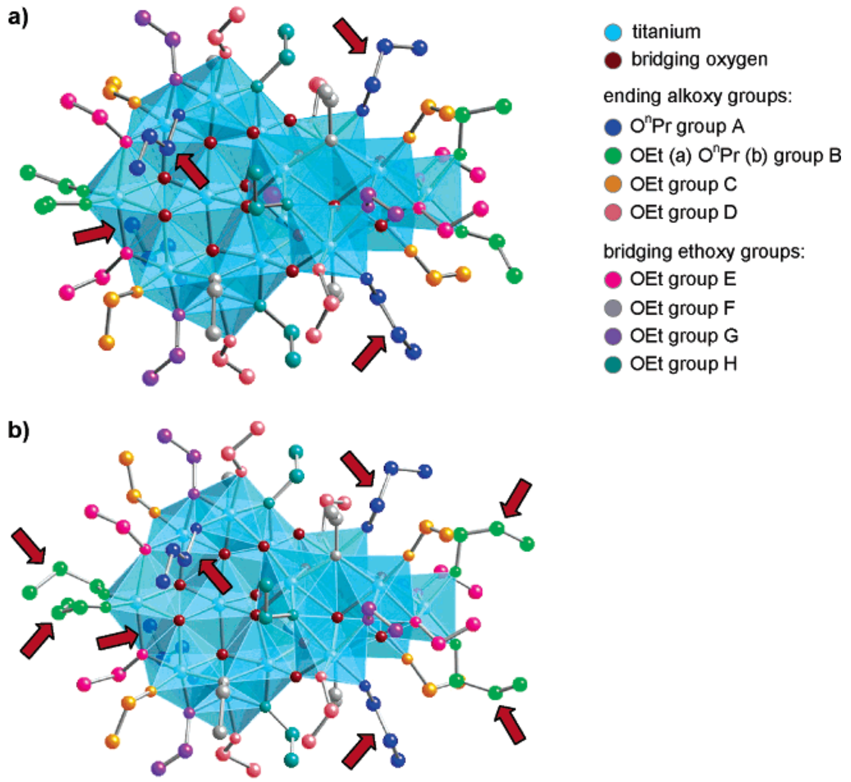

Figure 4. Representation of propoxy-modified *Ti*$_{16}$ in molecular form. (a) $Ti_{16}O_{16}(OEt)_{28}(O^nPr)_4$. (b) $Ti_{16}O_{16}(OEt)_{24}(O^nPr)_8$.

the more electrophilic character of some titanium atoms, which more easily undergo nucleophilic attack.

The same approach outlined above was applied to other alkyl alcohols (MeOH/methanol, *i*-PrOH/*i*-propanol, and *n*-BuOH/*n*-butanol). The kinetics of the exchange reactions and the degrees of substitution were studied by ^1H, ^{13}C NMR of the *Ti*$_{16}$ in solution with the various alcohols at the same ratio (alcohol/*Ti*$_{16}$ = 64:32) by integration of ^1H signals of released ethanol.

The results are summarized in Figure 5. Reaction kinetics depend on the nature of the alcohol, in particular kinetics scales with acidity (i.e., reagents with smaller pK_a promote faster substitution). This can be explained by the mechanism of the

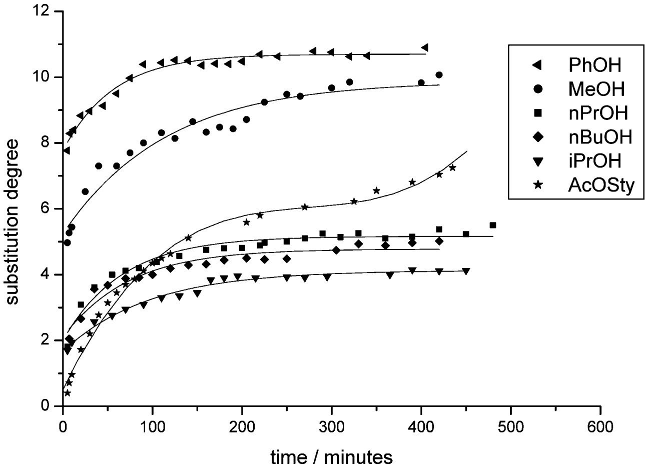

Figure 5. Kinetics of exchange with hydroxyl compounds. Substitution degree (number of substituted ethoxides/cluster) vs time (minutes). PhOH = phenol, MeOH = methanol, nPrOH = *n*-propanol, *n*BuOH = *n*-butanol, *i*PrOH = *i*-propanol, AcOSty = 4-acetoxystyrene.

transalcoholysis reaction. It is a nucleophilic substitution involving a nucleophilic addition followed by proton transfer from the attacking molecule to the leaving ethoxy group.[3b] Therefore, the acidity of the entering species favors this proton transfer promoting the substitution reaction.

The reactivity of *Ti₁₆* toward primary alcohols (*n*-PrOH and *n*-BuOH, $pK_a = 16.1$) follows the same general trend. Substitution is faster for the smaller substitutes, that is, substitution rate *n*-PrOH > *n*-BuOH; however, the sequence of substitution is the same (first the NMR signal 2 disappears for the signal 2′ followed by disappearance of the signal 5 to obtain the signal 5′). Also, the maximum substitution degree, equal to 8, is unchanged. The product recovered after 3 days is $Ti_{16}O_{16}(OEt)_{24}(OR)_8$ (with R = ^{n}Pr, ^{n}Bu), with the modification being fully reversible upon treatment with ethanol.

Secondary alcohols (*i*-propanol) have lower acidity ($pK_a = 17.1$) and larger steric hindrance. In this case, the substitution of the ethoxy groups by *i*-propoxides is slower than those observed for *n*-propanol or *n*-butanol (i.e., less than eight substituted positions have been modified in the same range of time).

On the other hand, the methanol, smaller and more acidic ($pK_a = 15.0$), leads to a higher substitution rate. It takes less than 5 min to exchange four ethoxides with methanol, while for the other alkyl alcohols, more than 1 h is required. Moreover, a substitution degree of about 10 ethoxides has been displayed by NMR measurements after 3 h.

The formation of new $Ti_{16}O_{16}(OEt)_{24}(OR')_8$ clusters by reaction with aliphatic alcohols can also be extended to more complex alcohols. We took into account two hydroxyl compounds bearing an aromatic derivative (benzyl alcohol, $PhCH_2OH$) and a nonaromatic (4-cyclohexyl-1-butanol, ${}^cCH_{11}{}^nBuOH$). In these cases, the transalcoholysis reaction proceeded as previously with the replacement of eight ethoxides (${}^{13}C$ peaks 2 and 5).

2.2. Exchange with Phenols. The reactivity toward a more acidic hydroxyl compound, in this case phenol ($pK_a = 9.9$), has also been studied. As expected by the previous observations, the exchange reaction is faster with phenol than with alkyl alcohols, leading to a higher degree of substitution in which 16 ethoxy groups are exchanged.

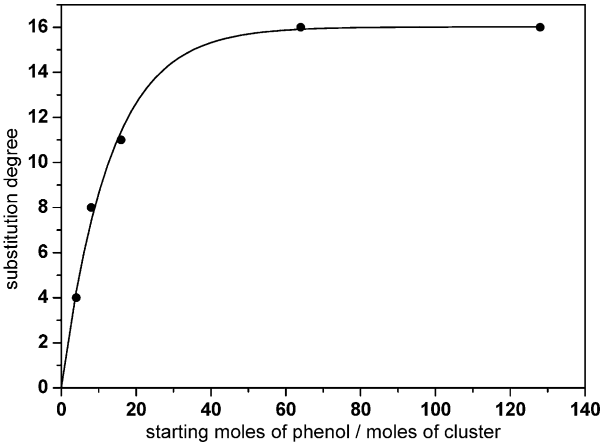

Figure 6. Exchange with phenols (50 °C for 3 days). Substitution degree (number of substituted ethoxides/cluster) vs starting moles of phenol/mole of cluster.

With a phenols/ethoxides ratio of 64:32, the exchange of the first eight ethoxides requires only 6 min (Figure 5), then the reaction slows down, almost certainly due to the steric hindrance of the phenoxy groups. Experiments using higher quantities of phenol achieved the exchange of 16 ethoxides (Figure 6) within 3 days, probably meaning that all the terminal ethoxide groups have been substituted.

It is possible with smaller quantities of phenol to isolate the $Ti_{16}O_{16}(OEt)_{28}(OPh)_4$ and $Ti_{16}O_{16}(OEt)_{24}(OPh)_8$ derivatives (Figure 7), but the NMR attribution of the modified positions is not as simple as with alkyl alcohols, since the electronic effects of the phenoxy groups are different from those of the ethoxy ligands and cause a shift of all the NMR signals. Nevertheless, spectra with good definition of the signals have been obtained for the symmetric clusters [$Ti_{16}O_{16}(OEt)_{28}(OPh)_4$ and $Ti_{16}O_{16}(OEt)_{24}(OPh)_8$], in agreement with the expected structures (Figure 7). Preservation of the oxo titanium core was confirmed by ${}^{17}O$ NMR of the 4- and 8-substituted samples (experiments recorded on the ${}^{17}O$ enriched *Ti₁₆*). Both spectra show the expected signals of μ_2O, μ_3O, and μ_4O. The chemical shifts and the integration ratios give proof of the preservation of the *Ti₁₆* structure.

To obtain a polymerizable titanium cluster, the reactivity toward 4-hydroxystyrene has been studied. The exchange reaction showed kinetics similar to phenol reaction, but we also noticed the concurrent polymerization of the vinylic function leading to the formation of a gel. Additionally, we considered the reaction with the corresponding ester (4-acetoxystyrene, AcOSty). The Lewis acidic behavior of titanium allows it to exchange ethoxides by a transesterification reaction leading to the same results as those obtained with phenols (up to 16 ethoxides exchanged) with a substitution rate that is slower and with no observed organic polymerization (Figure 5).

3. Complete Assignment of the Spectroscopic Data for $Ti_{16}O_{16}(OEt)_{32}$. A coherent indexation of ${}^1H$ and ${}^{13}C$ peaks for $Ti_{16}O_{16}(OEt)_{32}$ has been done previously;[10c] however, their complete assignment to the alkoxy groups localized in the crystallographic structure (indexed from A to H) has not been presented. To study more precisely the reactivity of the oxo alcoxo cluster $Ti_{16}O_{16}(OEt)_{32}$, this assignment is necessary.

Terminal or bridging ethoxy groups cannot be differentiated solely on the basis of their ${}^1H$ or ${}^{13}C$ chemical shift ranges

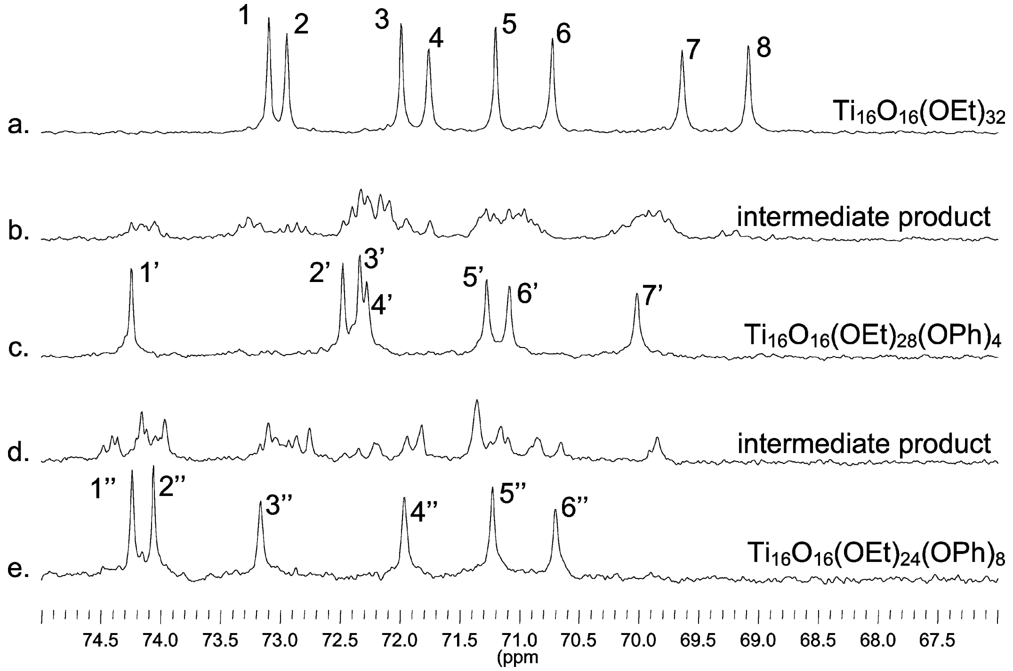

Figure 7. Kinetics of transalcoholysis reaction with phenol. Methylene region of ^{13}C spectra at 50 °C at different times and after introduction of different quantities of phenol: (a) before introduction, (b) +8 mol of phenol to 32 mol of ethoxide groups, (c) +16 mol of phenol to 32 mol of ethoxide groups, (d) +32 mol of phenol to 32 mol of ethoxide groups, and (e) +64 mol of phenol to 32 mol of ethoxide groups.

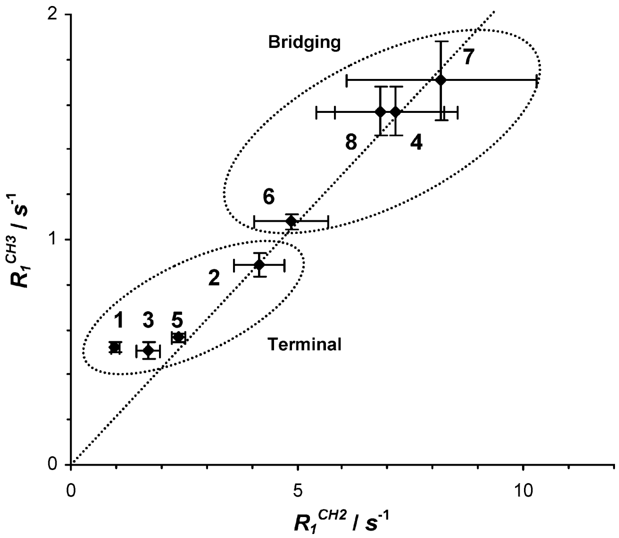

Figure 8. Methyl ^{13}C longitudinal relaxation rates R_1^{CH3} as a function of methylene ^{13}C longitudinal relaxation rates R_1^{CH2}. The error bars shown here were the result of the least-squares fits used for R_1 determination.

Table 2. The Closest Methyl Groups of *Ti$_{16}$*[a]

methyl groups	C–C distances (Å)
Terminal ↔ Terminal	
B−B	4.35
B−C	4.78
Terminal ↔ Bridging	
C−G	3.89
A−H	3.95
B−G	4.11
D−F	4.46
C−E	4.49
C−F	4.51
B−G	4.63
D−E	4.68
Bridging ↔ Bridging	
F−H	4.00
G−E	4.13
E−H	4.83
E−F	4.88

[a] Methyl carbon−carbon internuclear distances below 5 Å taken from the crystallographic structure of *Ti$_{16}$* in tetragonal form.[8] Spatial proximities between terminal and/or bridging ethoxy groups are differentiated.

because those are often superimposed.[10c] The measurement of their ^{13}C NMR longitudinal relaxation rates R_1 may be of help for this task. In Figure 8, we observe that the ^{13}C relaxation rates of the methyl groups R_1^{CH3} are correlated to those of the methylene groups R_1^{CH2} with a ratio (R_1^{CH3}):(R_1^{CH2}) close to 1:5. Considering intramolecular ^{1}H−^{13}C dipole−dipole interactions as the main mechanism of relaxation, the value of this ratio cannot be understood in the frame of isotropic fast motion of the molecule (ratio expected 3:2). However, the overall motion of a large molecule such as *Ti$_{16}$* is slower than a single small molecule and is probably slower than the internal motions of the ethoxy groups. For macromolecules (see, for example, Lipari Szabo, 1982), the spectral density functions $J(\omega)$ depend on the rate and on the spatial restrictions of the internal motions. The methylene groups that are closer to the binding point on the *Ti$_{16}$* cluster than the methyl groups have slower and more restricted motions. Therefore, their related spectral density functions $J(\omega)$ and relaxation rates R_1 should have higher values, as observed in Figure 8. Similarly, slower and more restricted motions are expected for the bridging ethoxy groups compared to the terminal groups, and their ^{13}C nuclei would have higher R_1^{CH3} and R_1^{CH2} values. The bridging groups should correspond then to the signals indexed 4, 6, 7, and 8, and the terminal ethoxy groups to the signals 1, 2, 3, and 5. This is further supported by the assignment of signals 2 and 5 to the terminal ethoxy groups A and B, respectively, on the basis of the crystallographic structures of the *n*-propanol-substituted *Ti$_{16}$* and the related ^{13}C NMR spectra.

The assignment of the ^{1}H and ^{13}C peaks can be completed using the spatial proximities between ethoxy groups as measured

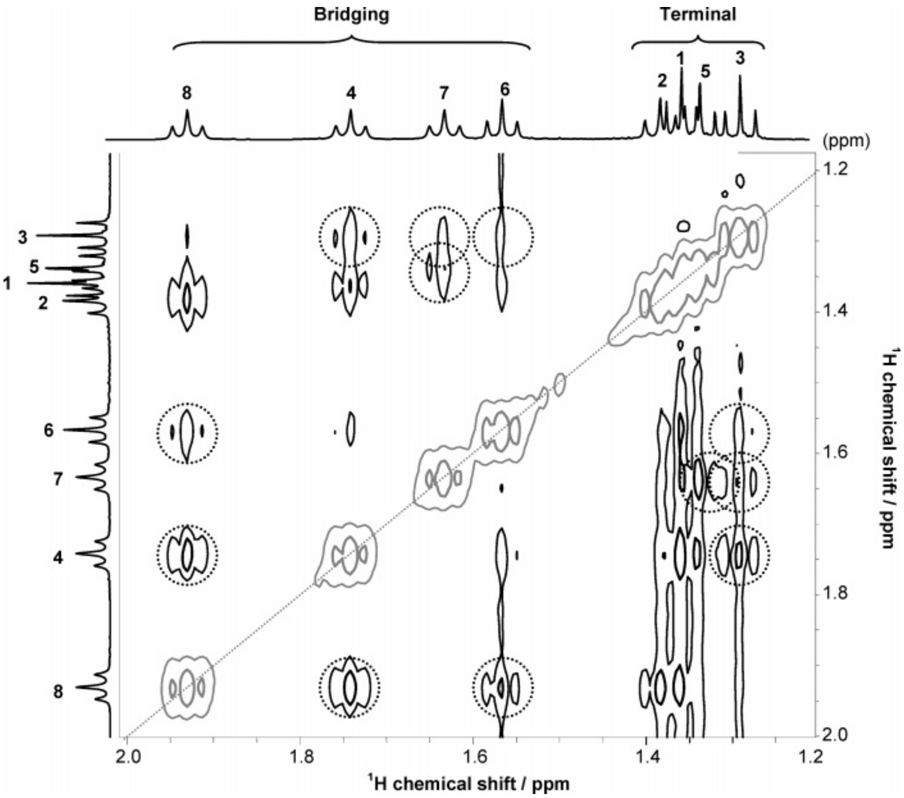

Figure 9. Zoomed area of a ^{1}H$-$^{1}H NMR ROESY experiment (mixing time: 0.3 s) showing the methyl$-$methyl correlations peaks: on-diagonal (positive, in gray) and off-diagonal (negative, in black). The dashed circles show the correlations used for the assignment of the NMR signals (Table 3).

Table 3. Complete Assignment of ^{1}H and ^{13}C NMR Signals of *Ti$_{16}$*[a]

stepped assignments	NMR correlations	spatial proximities
2 ≡ A and 5 ≡ B (initial)		
7 ≡ G	terminal 5 ↔ bridging 7	terminal B ↔ bridging G
3 ≡ C	bridging 7 ↔ terminal 3	bridging G ↔ terminal C
1 ≡ D (deducted)		
8 ≡ H (deducted)	terminal 3 ↔ bridging 4, 7, 6	terminal C ↔ bridging G, E, F
4 ≡ F and 6 ≡ E	bridging 8 ↔ bridging 4 (stronger) bridging 8 ↔ bridging 6 (weaker)	bridging H ↔ bridging F (closer) bridging H ↔ bridging E (farther)

[a] Successive steps used for the assignment of ^{1}H and ^{13}C NMR signals of *Ti$_{16}$* (indexed from 1 to 8) to the crystallographic positions of the ethoxy groups (indexed from A to H) using the ^{1}H$-$^{1}H NMR correlations observed in NOESY or ROESY experiments and the spatial proximities deducted from carbon$-$carbon internuclear distances. NMR relaxation data (see text) allowed distinguishing terminal ethoxy groups (signals 1, 2, 3, 5; positions A to D) from bridging ethoxy (signals 4, 6, 7, 8; positions E to H). The first assignments (2 ≡ A, 5 ≡ B) are obtained from propanol-substituted *Ti$_{16}$*.

in a crystallographic form of *Ti$_{16}$*, and as indirectly observed in ^{1}H$-$^{1}H 2D NMR experiments, NOESY,[19] or ROESY.[20] For the sake of simplicity, we present here the more useful data, that is: (i) the smallest methyl carbon$-$carbon internuclear distances measured in the tetragonal form[8] in which the *Ti$_{16}$* cluster bears the same symmetry as in solution (Table 2) and (ii) the area of a ^{1}H$-$^{1}H ROESY 2D spectrum showing the correlations between protons of the methyl groups (Figure 9). The successive steps used for the assignment are described in Table 3. The signals 7 and 3 are easily assigned to the bridging ethoxy G and the terminal ethoxy C. The last unassigned signal of the terminal ethoxy groups 1 is thus necessarily related to the ethoxy D. Signal 8, which gives no ^{1}H$-$^{1}H correlations with signal 3, is assigned to the bridging ethoxy group H that is the only bridging group far from the terminal group C. Last, on the basis of differences in correlation intensities and spatial proximities with respect to signal 8 and ethoxy group H, signals 4 and 6 are assigned to bridging ethoxy groups F and E, respectively.

Conclusion

This work shows the versatility of the oxo alcoxo titanium cluster. As a function of the nature of the studied alcohols, different clusters can be easily synthesized with preservation of the titanium oxo core. The controlled modification of the organic shell of the cluster via transalcoholysis or transesterification reactions leads to new clusters $Ti_{16}O_{16}(OEt)_{32-x}(OR)_x$. The kinetics of the substitution reaction and the degree of substitution can be adjusted ($x = 4, 8, 16$) by tuning the nature of the alcoholic reagent (Table 4). With linear aliphatic alcohols (such as *n*-propanol and *n*-butanol), only eight ethoxy can be exchanged; when the pK_a of the alcohol is lower (methanol), the degree of substitution increases. For sterically hindered alcohols (*i*-propanol), the substitution is less effective. In the case of more acidic reactants (phenol), all the terminal ethoxy groups are exchanged by phenoxy ligands, yielding a new $Ti_{16}O_{16}(OEt)_{16}(OPh)_{16}$ cluster. The intermediate clusters [$Ti_{16}O_{16}$-

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(19) (a) Jeener, J.; Meier, B. H.; Bachmann, P.; Enrst, R. R. *J. Chem. Phys.* **1979**, *71*, 4546$-$4553. (b) Wagner, R.; Berger, S. *J. Magn. Reson.* **1996**, *123A*, 119$-$121.

(20) Bax, A.; Davis, D. G. *J. Magn. Reson.* **1985**, *63*, 207$-$213.

Table 4. Summary of the Different Possible Substituted *Ti16* Clusters

R[a]	reactivity	$Ti_{16}O_{16}(OEt)_{28}(O\mathbf{R})_4$	$Ti_{16}O_{16}(OEt)_{24}(O\mathbf{R})_8$	$Ti_{16}O_{16}(OEt)_{16}(O\mathbf{R})_{16}$
Me	++		×	
^{n}Pr	+	×	×	
^{n}Bu	+	×	×	
^{i}Pr	−			
$PhCH_2$	+	×	×	
$^cC_6H_{11}{}^n$Bu	+		×	
Ph	+++	×	×	×
$CH_2{=}CHPh$	+++	×	×	×

[a] Me = methyl, ^{n}Pr = *n*-propyl, ^{n}Bu = *n*-butyl, ^{i}Pr = *i*-propyl, Ph = phenyl, $^cC_6H_{11}$ = cyclohexyl.

$(OEt)_{28}(O^nPr)_4$, $Ti_{16}O_{16}(OEt)_{28}(OPh)_4$, and $Ti_{16}O_{16}(OEt)_{24}(OPh)_8$] have been isolated and characterized by NMR spectroscopy and some of them by crystallographic analysis.

Moreover, a complete assignment of each ethoxy ligand has been realized by the use of 2D NMR measurements, leading to perfect knowledge of the organic surface of the *Ti16* cluster.

A strong modification of the organic shell can be achieved to increase the dispersion of the modified cluster in an organic media (4-cyclohexyl-1-butanol). It is also possible to elaborate clusters that exhibit polymerizable functions such as styrenic functions to connect them by covalent bonds to an organic matrix.

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Supporting Information Available: Crystallographic data of $Ti_{16}O_{16}(OEt)_{28}(O^nPr)_4$ and $Ti_{16}O_{16}(OEt)_{24}(O^nPr)_8$ (CIF). This material is available free of charge via the Internet at http://pubs.acs.org.

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