Early Transition Metal Alkoxide Complexes Bearing Homochiral Trialkanolamine Ligands

William A. Nugent* and Richard L. Harlow

Contribution No. 6806 from The DuPont Company, Central Research and Development, P.O. Box 80328, Wilmington, Delaware 19880-0328

*Received February 2, 1994**

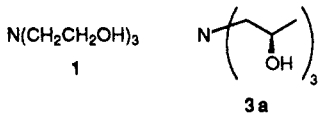
Abstract: Enantiomerically pure trialkanolamines of the formula $N(CH_2CHROH)_3$, where R = methyl (**3a**), cyclohexyl (**3b**), *tert*-butyl (**3c**), or phenyl (**3d**), are readily synthesized by the reaction of ammonia with 3 equiv of an enantiopure epoxide. Trialkanolamines **3a–d** replace *n*-propanol in tri-*n*-propyl vanadate to afford corresponding complexes **4a–d** of the formula LV=O, where L is the deprotonated trialkanolamine. Similarly, (*S*,*S*,*S*)-triisopropanolamine **3a** reacts with $Ti(O^iPr)_4$ to produce monomeric $LTi(O^iPr)$, **7a**, which upon treatment with acetyl chloride gives the chloro complex LTiCl, **7b**. The later group 5 ethoxides react with **3a** to produce $LM(OEt)_2$ (M = Nb, Ta). Partial hydrolysis of the Nb and Ta derivatives produces tetrameric μ-oxo-bridged structures which retain the trialkanolamine ligands. In all complexes the transition metal resides in a highly asymmetric environment, suggesting that this class of complexes may find use in the field of asymmetric catalysis. The X-ray crystal structures of complexes **4c** and **7b** are reported.

Early transition metal complexes bearing chiral alkoxide ligands are widely employed as asymmetric catalysts.[1-10] With few exceptions,[1b,11] the early transition metal used in these catalysts has been titanium. For an alkoxide ligand to function effectively in such applications, it must remain attached to the metal under the reaction conditions, even after many catalytic cycles. This can be difficult when reactions are run in the presence of excess silylating agents or other oxophilic reagents.

Several strategies have been used to address this problem. For example, binaphthol ligands[12] take advantage of the higher K_a of phenols versus alcohols to provide a *thermodynamic* stabilization of the metal ligand bonds. There is also some evidence that in certain cases steric bulk can be used to *kinetically* retard the loss of a coordinating alkoxide. For example, a catalyst prepared from titanium isopropoxide and diisopropyl tartrate promotes the enantioselective addition of azidotrimethylsilane to cyclohexene oxide when used stoichiometrically but produces only racemic product when used catalytically.[7b] However, Oguni has recently demonstrated that the bulkier di-*tert*-butyl tartrate can be used to provide a reaction which is both enantioselective and catalytic.[7a]

To date, the most successful strategy for preparing robust early transition metal alkoxides for use as enantioselective catalysts has been the use of diols or polyols so that the catalytic species is stabilized via chelation. A familiar example is the Sharpless asymmetric epoxidation[1a] which utilizes bidentate diolate ligands derived from dialkyl tartrates. In fact we know of no reaction in which high enantioselectivity (>70% ee) has been achieved using a transition metal[13] catalyst bearing monodentate alkoxide ligands. Many of the chelating alkoxide ligands in the literature also possess C_2 symmetry. The advantages of C_2 symmetric ligation have been reviewed by Whitesell.[14]

We have been investigating a novel series of chelating (tetradentate) chiral alkoxide ligands, namely, homochiral[15] trialkanolamines. The ability of the parent triethanolamine, **1**, to stabilize titanium alkoxides toward hydrolysis in aqueous environments has been recognized for some time.[16]



Complexes containing the trianion of **1** coordinated to a variety of early transition metals have been synthesized.[17] In particular, Verkade[18] has recently structurally characterized titanium complexes of ligand **1**. We were somewhat surprised that, prior to our studies, no transition metal alkoxides derived from

* Abstract published in *Advance ACS Abstracts,* June 1, 1994.

(1) For asymmetric epoxidation: (a) Gao, Y.; Hanson, R. M.; Klunder, J. M.; Ko, S. Y.; Masamune, H.; Sharpless, K. B. *J. Am. Chem. Soc.* **1987**, *109*, 5765. (b) Ikegami, S.; Katsuki, T.; Yamaguchi, M. *Chem. Lett.* **1987**, 83.

(2) Oxidation of sulfides: Pitchen, P.; Dunach, E.; Deshmukh, M. N.; Kagan, H. B. *J. Am. Chem. Soc.* **1984**, *106*, 8188.

(3) Silylcyanation of aldehydes: Callant, D.; Stanssens, D.; de Vries, J. G. *Tetrahedron: Asymmetry* **1993**, *4*, 185. Hayashi, M.; Matsuda, T.; Oguni, N. *J. Chem. Soc., Perkin Trans. 1* **1992**, 3135.

(4) Diels–Alder reaction: Maruoka, K.; Murase, N.; Yamamoto, H. *J. Org. Chem.* **1993**, *58*, 2938. Devine, P. N.; Oh, T. *J. Org. Chem.* **1992**, *57*, 356. Narasaka, K.; Iwasawa, N.; Inoue, M.; Yamada, T.; Nakashima, M.; Sugimori, J. *J. Am. Chem. Soc.* **1989**, *111*, 5340.

(5) Ene reaction: Mikami, K.; Sawa, E.; Terada, M.; Nakai, T. *Tetrahedron Lett.* **1991**, *32*, 6571. Mikami, K.; Shimizu, M. *Chem. Rev.* **1992**, *92*, 1021.

(6) 1,2-Alkyl addition to aldehydes: Keck, G. E.; Tarbet, K. H.; Geraci, L. S. *J. Am. Chem. Soc.* **1993**, *115*, 8467. Costa, A. L.; Piazza, M. G.; Tagliavini, E.; Tombini, C.; Umani-Ronchi, A. *J. Am. Chem. Soc.* **1993**, *115*, 7001. Seebach, D.; Plattner, D. A.; Beck, A. K.; Wang, Y. M.; Hunziker, D. *Helv. Chim. Acta* **1992**, *75*, 2171. It is noteworthy that amino alcohols have proven to be effective ligands for the asymmetric addition of organozinc reagents to carbonyl compounds; for a review see: Noyori, R.; Kitamura, M. *Angew. Chem., Int. Ed. Engl.* **1991**, *30*, 49.

(7) Addition of nucleophiles to meso epoxides: (a) Hayashi, M.; Kohmura, K.; Oguni, N. *Synlett* **1991**, 774. (b) Emziane, M.; Sutowardoyo, K. I.; Sinou, D. *J. Organomet. Chem.* **1988**, *346*, C7. (c) See also ref 11a.

(8) 2 + 2 Cycloaddition: Hayashi, Y.; Narasaka, K. *Chem. Lett.* **1989**, 1919. *Ibid.* **1990**, 1295.

(9) Aldol reaction: Reetz, M. T.; Kyung, S.-H.; Bolm, C.; Zierke, T. *Chem. Ind.* **1986**, 824.

(10) Ester hydrolysis: Narasaka, K.; Kanai, F.; Okudo, M.; Miyoshi, N. *Chem. Lett.* **1989**, 1187.

(11) (a) Nugent, W. A. *J. Am. Chem. Soc.* **1992**, *114*, 2768. (b) Nugent, W. A. U.S. Patent 5,231,203, 1993. (c) Nugent, W. A.; RajanBabu, T. V.; Burk, M. J. *Science* **1993**, *259*, 479. (d) Nugent, W. A.; Feldman, J.; Pittman, A. Unpublished results.

(12) For a review of chiral Lewis acid catalysts including many examples utilizing binaphthol ligands see: Narasaka, K. *Synthesis* **1991**, 1.

(13) For an example in which a monodentate alkoxide on a main group metal (aluminum) provides a 72% ee in a Diels–Alder reaction see: Hashimoto, S.; Komeshima, N.; Koga, K. *J. Chem. Soc., Chem. Commun.* **1979**, 437. Takemura, H.; Komeshima, M.; Takahashi, I.; Hashimoto, S.; Ikota, N.; Tomioka, K.; Koga, K. *Tetrahedron Lett.* **1987**, *28*, 5687.

(14) Whitesell, J. K. *Chem. Rev.* **1989**, *89*, 1581.

(15) The term "homochiral" is used herein according to its original definition; i.e. that the three arms of the trialkanolamine ligand are of the same absolute configuration.

(16) The commercial titanate "Tyzor TE" sold by the DuPont Co. utilizes triethanolamine to provide stability in moist environments. Bostwick, C. O. U.S. Patent 2,824,114, 1958.

0002-7863/94/1516-6142$04.50/0

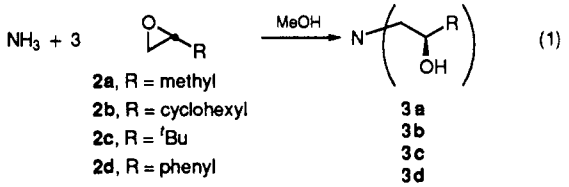
enantiopure homochiral triisopropanolamine **3a** or its higher homologues had been reported.[19-21] Nevertheless, a boron derivative of **3a** was known,[22] and we were further encouraged by the report of Morrison,[23] who used **3a** as a chiral auxiliary in stoichiometric lithium aluminum hydride reductions.

Our initial interest in **3a** and related ligands also reflected the fact that they possess C_3 symmetry. Burk[24] has eloquently stated the potential advantages of C_3 symmetry ligands in asymmetric catalysis, in particular the possibility that such ligands can provide three identical coordination sites within an octahedral coordination geometry. However, this argument is not strictly applicable to complexes of **3a** and its homologues wherein the donor nitrogen atom strongly favors tetrahapto coordination.

In preliminary studies we have reported that zirconium species bearing the parent triisopropanolamine ligand **3a** catalyze the highly enantioselective cleavage of meso epoxides with azidotrialkylsilanes.[11] However, we were frustrated in these studies by the fact that the zirconium and hafnium derivatives of **3a** were very complex oligomeric species which thus far have defied detailed characterization. In this paper we have explored the coordination chemistry of **3a** with the group 5 transition metals and with titanium and find that each of these metals forms discrete complexes, which we have fully characterized. We have also extended the series of enantiopure trialkanolamines to include the cyclohexyl, *tert*-butyl, and phenyl analogues **3b–d**. We expect that these results will facilitate the development of additional useful catalysts on the basis of these readily available ligands.

Results and Discussion

Synthesis of Homochiral Trialkanolamines. The preparation of (*S*,*S*,*S*)-triisopropanolamine from ammonia and (*S*)-propylene oxide was previously reported by Morrison.[23] We find that it is especially convenient to carry out this transformation using commercially available 2 M ammonia in methanol solution. This procedure (eq 1) can also be applied to the synthesis of the cyclohexyl, *tert*-butyl, and phenyl analogues **3b–d**. In this



(1)

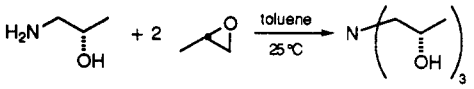
2a, R = methyl
2b, R = cyclohexyl
2c, R = ^{t}Bu
2d, R = phenyl

3a
3b
3c
3d

approach 3 equiv of an enantiopure epoxide is dissolved in 1 equiv of NH_3/methanol and allowed to stand overnight. The mixture is then heated for several days at 40–50 °C to ensure complete reaction. (See the Experimental Section for details.) The regioselectivity for addition of amine to the terminal carbon atom is very high for epoxides **2a–c**. The corresponding trialkanolamines **3a–c** can be isolated in analytically pure form by removal of the solvent at reduced pressure.

In the case of styrene oxide (**2d**), attack at the benzylic carbon atom competes with attack at the terminal position, resulting in the formation of isomeric trialkanolamines. The desired **3d** is easily separated from the other isomers by flash chromatography. However, this limits the yield of **3d** to ca. 40%.

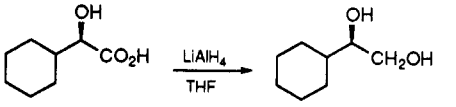
We have also developed a convenient alternative route to **3a**. Thus, treatment of a toluene solution of (*S*)-1-amino-2-propanol with 2 equiv of (*S*)-propylene oxide proceeds according to eq 2.



(2)

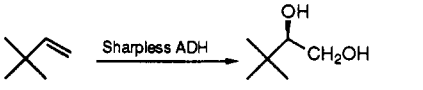
NMR studies in benzene-d_6 indicate that this reaction is essentially complete after 6 days at room temperature. In many cases **3a** spontaneously separates from solution as large transparent crystals. Otherwise, crystallization is readily initiated (Experimental Section).

Of the epoxides used in these studies, **2a** and **2d** are commercially available in both optical antipodes. Preparation of the cyclohexyloxiranes (*S*)- and (*R*)-**2b** begins with lithium aluminum hydride reduction of the appropriate enantiomer of hexahydromandelic acid to afford the diol (eq 3) following the procedure of Riley.[25] Similarly a diol precursor for *tert*-butyl



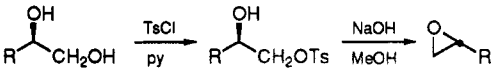
(3)

oxirane **2c** could be prepared, in this case via the Sharpless asymmetric dihydroxylation[26] (eq 4). Although the diol was initially formed in only 80% ee, optically pure material was readily obtained by two recrystallizations from toluene at −25 °C. The



(4)

diol products from eqs 3 and 4 were converted to the corresponding epoxides **2b** and **2c** via the monotosylates (eq 5).



(5)

An alternative approach to the cyclohexyl derivative **3b** involved the hydrogenation of the phenyl rings of **3d**. This hydrogenation proceeds readily at room temperature in ethyl acetate solvent over 5% platinum oxide on alumina catalyst.

Oxovanadium(V) Complexes. Vanadium complexes of ligands **3a–d** were particularly easy to isolate as a result of their low solubility in ethereal solvents. Following eq 6, a solution of a given trialkanolamine was added dropwise to a slight excess of tri-*n*-propyl vanadate in ether or THF. The resultant complexes **4a–d** precipitated from solution as white solids, and the last traces of solvent were removed in high vacuum.

(17) (a) Harlow, R. L. *Acta Crystallogr.* **1983**, *C39*, 1344. (b) Taube, R.; Knoth, P. *Z. Anorg. Allg. Chem.* **1990**, *581*, 89. (c) Astakhov, A. I.; Kas'yanenkp, A. I. *Izv. Vyssh. Uchebn. Zaved. Khim. Khim. Tekhnol.* **1972**, *15*, 1620; *Chem. Abstr.* **1973**, *78*, 66407. (d) Mehrota, R. C.; Kapoor, P. N. *J. Indian Chem. Soc.* **1967**, *44*, 467. (e) Mehrota, R. C.; Kapoor, P. N. *Indian J. Chem.* **1967**, *5*, 5051. (f) Cohen, H. J. *J. Organomet. Chem.* **1967**, *9*, 177.

(18) (a) Menge, W. M. B. P.; Verkade, J. G. *Inorg. Chem.* **1991**, *30*, 4628. (b) Naiini, A.; Menge, W. M. B. P.; Verkade, J. G. *Inorg. Chem.* **1991**, *30*, 5009. (c) Naiini, A. A.; Ringrose, S. L.; Su, Y.; Jacobson, R. A.; Verkade, J. G. *Inorg. Chem.* **1993**, *32*, 1290.

(19) For diastereomeric mixtures of transition metal alkoxides prepared from racemic triisopropanolamine: Tandura, S. N.; Voronkov, M. G.; Kisin, A. V.; Shestakov, E. E.; Ovchinnikova, Z. A.; Baryshok, V. P. *Zh. Obshch. Khim.* **1984**, *54*, 2010. Voronkov, M. G.; Faitel'son, F. D. *Khim. Geterotsikl. Soedin.* **1967**, 39; *Chem. Abstr.* **1967**, *67*, 64321.

(20) Recently Crans and co-workers have prepared and structurally characterized an oxovanadium(V) complex bearing homochiral but racemic triisopropanolamine ligands: (a) Crans, D. C.; Chen, H.; Anderson, O. P.; Miller, M. M. *J. Am. Chem. Soc.* **1993**, *115*, 6769. (b) Crans, D. C.; Ehde, P. M.; Shin, P. K.; Pattersson, L. *J. Am. Chem. Soc.* **1991**, *113*, 3728.

(21) For a titanium complex bearing an enantiopure trialkanolamine ligand with a single asymmetric carbon atom see: Liu, H.; Yin, C. *Gaodeng Xuexiao Huaxue Xuebao* **1989**, *10*, 1257; *Chem. Abstr.* **1990**, *113*, 125232.

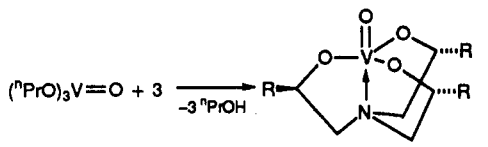
(22) Grassi, M.; Di Silvestro, G.; Farina, M. *Tetrahedron* **1985**, *41*, 177.

(23) Morrison, J. D.; Grandbois, E. R,; Weisman, G. R. In *Asymmetric Reactions and Processes in Chemistry*; Eliel, E. L., Otsuka, S., Eds.; ACS Symposium Series 185; American Chemical Society: Washington, DC, 1982.

(24) Burk, M. J.; Harlow, R. L. *Angew. Chem., Int. Ed. Engl.* **1990**, *29*, 1462.

(25) Riley, D. P.; Shumate, R. E. *J. Org. Chem.* **1980**, *45*, 5187.

(26) Sharpless, K. B.; Amberg, W.; Beller, M.; Chen. H.; Hartung, J.; Kawanami, Y.; Luebben, D.; Manoury, E.; Ogino, Y.; Shibata, T.; Ukita, T. *J. Org. Chem.* **1991**, *56*, 4585.



4a, R = methyl
4b, R = cyclohexyl
4c, R = ^{t}Bu
4d, R = phenyl
4e, R = H

It should be noted that the type of exchange required for eq 6 has been characterized in detail by Crans and co-workers for a related achiral system using ESXY spectroscopy.[20] Their studies also revealed that coordination of alcohols to the metal atom in these systems is very sensitive to the sterics of the alcohol function (no complex is formed between *tert*-butyl alcohol and racemic **3a**).[20a]

For all four complexes **4a–d**, the NMR spectra were consistent with the trigonal bipyramidal structure of C_3 symmetry as indicated. In all complexes the three arms of the trialkanolamine ligand were equiv by both ^{1}H and ^{13}C NMR. The OCH resonance in the ^{1}H NMR shifted downfield by approximately 1.0 ppm versus the free ligand. A somewhat smaller downfield shift in the range 0.4–0.8 ppm was observed for the CH_2N resonances. The CH_2N protons typically appear as two doublets of doublets. The upfield resonance of this pair shows a large geminal coupling (ca. 13 Hz) and a large vicinal coupling (ca. 12 Hz), consistent with a conformation in which this hydrogen is located *anti* to the OCH hydrogen. As expected, the vicinal coupling for the downfield CH_2N resonance is much smaller (4–5 Hz), consistent with its location *gauche* to the OCH hydrogen. This interpretation is supported by the structural studies described below.

We have determined the structure of complex **4c** by X-ray crystallography. An ORTEP representation of **4c** is shown in Figure 1, and key bond distances and angles are summarized in Table 1. Also shown in Table 1 are the corresponding data for racemic **4a** and for the parent triethanolamine complex **4e** recently reported by Crans.[20] As expected, the **4c** molecule exhibits pseudo-3-fold symmetry and an approximately trigonal bipyramidal coordination geometry. As is the case in **4a** and **4e**, the geometry of **4c** is distorted toward a tetrahedral structure; the vanadium is displaced from the plane of the three alkoxide oxygens by 0.35 Å.

As this molecule assembles itself, two options exist for the placement of the three *tert*-butyl groups. In principle either these could locate themselves proximal to vanadium in positions equivalent to those occupied by the hydrogen atoms bound to C11, C21, and C31 or they can be located distal to the vanadium atom, as is actually observed here and also in the methyl substituents of complex **4a**.[20] Once this choice has been made, this configuration is effectively locked in place by its rigid tricyclic structure.

The observed structure has implications for the use of **4c** and related complexes in enantioselective catalysis. In particular, the distal relationship of the *tert*-butyl group with respect to the vanadium atom effectively eliminates any *direct* impact of this substituent in creating a chiral environment in the coordination sphere of the vanadium atom. Rather, the asymmetry of the coordination sphere of **4c** is mainly imparted by the set of hydrogen atoms attached to C11, C21, and C31, which are arranged in a clockwise array around the equatorial plane of the complex. Moreover, Table 1 suggests that the bulky *tert*-butyl substituent has little *indirect* effect on the coordination sphere of vanadium. The data in Table 1 allow us to examine changes in the coordination sphere of complexes **4** as the steric bulk of the alkyl substituent increases along the series R = H, methyl, *tert*-butyl. These data confirm that the inner coordination sphere is essentially

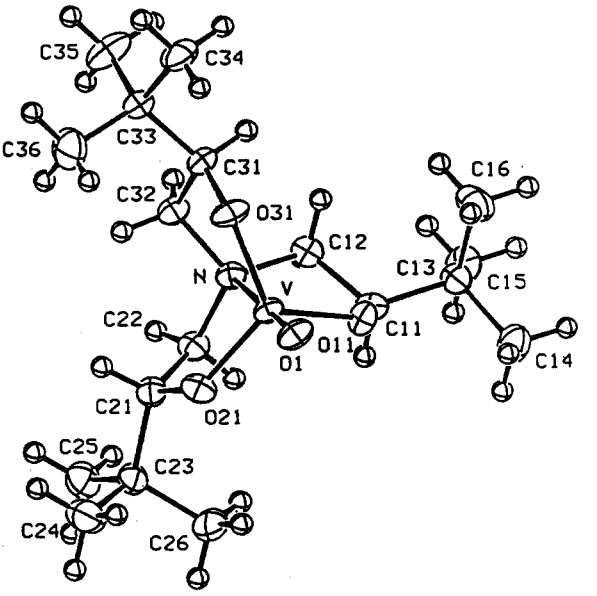


Figure 1. ORTEP drawing of complex (*R,R,R*)-**4c** showing the numbering system.

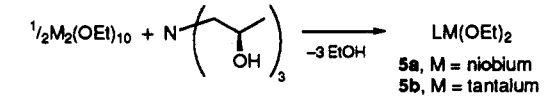
Table 1. Comparison of Bond Distances (Å) and Angles (deg) in the Coordination Sphere of **4a**,[a] **4e**,[a] and **4c**

bonds	re	(±)-4a[b]	(*R,R,R*)-4c
	Distances		
V=O	1.633(6)	1.617(13)	1.612(2)
V–O(C)	1.793(4)	1.794(4)	1.810(2)
	1.797(4)		1.803(2)
	1.792(4)		1.799(2)
V–N	2.276(7)	2.297(15)	2.269(3)
O–C	1.425(8)	1.456(10)	1.429(4)
	1.416(8)		1.423(4)
	1.427(7)		1.428(4)
	Angles		
O=V–O(C)	99.9(2)	101.0(2)	101.0(1)
	99.4(2)		101.3(1)
	100.9(2)		100.9(1)
O–V–N	179.2(2)	180[b]	179.5(7)
V–N–C	105.4(4)	105.3(6)	104.8(2)
	105.4(4)		106.1(2)
	104.7(4)		105.3(2)

[a] Data for complexes **4a** and **4e** from ref 20. [b] The complex has crystallographically imposed 3-fold symmetry.

superimposable for these three complexes. (In fact, the same can be said of the chlorotitanium derivative **7b** below.) On the basis of these results we focused on the parent triisopropanolamine ligand **3a** in the remainder of the studies reported below.

Niobium and Tantalum Complexes. Treatment of a THF solution of niobium(V) ethoxide with 1 equiv of ligand **3a** followed by distillation of solvent and by-product ethanol afforded the triisopropanolamine complex **5a** following eq 7. The corresponding reaction with tantalum(V) ethoxide proceeded in an identical manner to give **5b**. Both products were obtained as colorless, distillable liquids and in this regard resemble the related complexes bearing the parent ligand **1** which were reported a quarter century ago by Mehrota and Kapoor.[17d,e]



5a, M = niobium
5b, M = tantalum

The ^{1}H NMR for the OCH and NCH_2 region of **5a** in $CDCl_3$ solution at 25 °C is shown in Figure 2A. The noteworthy feature of this spectrum is the presence of a single set of resonances of both the ethoxide ligands and the three arms of the triisopro-

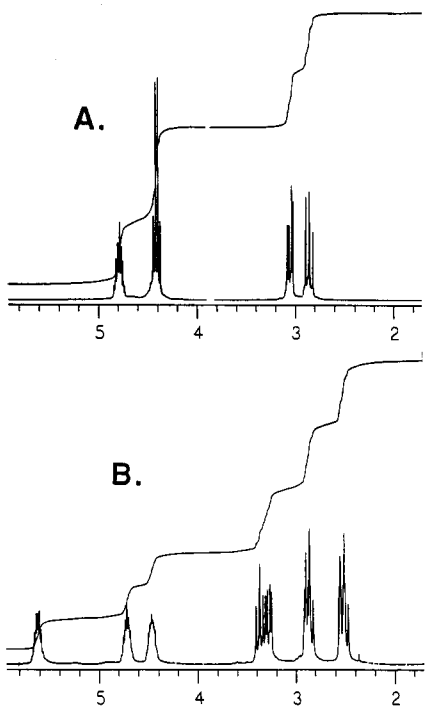


Figure 2. ^{1}H NMR (300 MHz, in $CDCl_3$) of the OCH and NCH_2 regions of (A) complex **5a** and (B) complex **6a**.

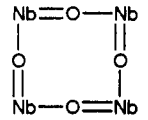
panolamine ligand. The ^{1}H NMR of **5b** shows a similar equivalence, which is also observed in the ^{13}C NMR spectra of the two complexes at ambient temperature. This striking observation is in fact consistent with the theoretical predictions. Eisenstein and co-workers have shown[27] that octahedral coordination geometry is not strongly favored in d^0 systems bearing poorly π-donating ligands. This opens the door to facile exchange processes which interconvert the ethoxide ligands in **5a** and **5b** on the NMR time scale.

The partial hydrolysis of these niobium and tantalum derivatives was also examined. (The literature contains several cases where partially hydrolyzed early transition metal alkoxides show enhanced catalytic activity relative to the parent alkoxides.[28]) Reaction of **5a** or **5b** with 1 equiv of water in THF proceeds according to eq 8. As expected,[29] the product in each case is not the terminal oxo derivative but rather a μ-oxo complex as indicated.

$$LM(OEt)_2 + H_2O \xrightarrow{THF} (LMO)_n + 2EtOH \qquad (8)$$

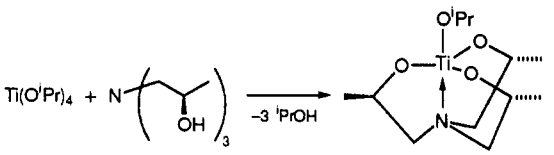
6a, M = niobium
6b, M = tantalum

The tetrameric nature of **6a** was gleaned via a preliminary X-ray structure.[30] The crystal utilized in this study had been grown in toluene and contained five toluene molecules per niobium tetramer. Severe disorder in the toluene molecules precludes detailed interpretation of the structure. Nevertheless, a planar array of four niobium atoms connected by unsymmetrical oxo bridges (and possessing crystallographic 4-fold symmetry) was clearly present:



The ^{1}H NMR spectrum of the niobium derivative **6a** in $CDCl_3$ at 25 °C is illustrated in Figure 2B. In this case three distinct sets of resonances are observed for the three arms of the triisopropanolamine. As expected, the presence of the μ-oxo bridges enforces an approximately octahedral coordination geometry by ruling out the exchange processes observed in **5a** and **5b**. We tentatively assign the two similar upfield sets of NCH_2 and OCH resonances to the two arms of the triisopropanolamine which occupy the axial positions in **6a**. The remaining downfield resonances would then correspond to the equatorial arm for which the alkoxide oxygen atom should be approximately coplanar with the metal, the bridging oxo ligands, and the nitrogen atom.

Titanium Complexes. Treatment of a THF solution of titanium(IV) isopropoxide with 1 equiv of (*S,S,S*)-**3a** proceeded with a loss of 3 equiv of isopropyl alcohol according to eq 9. Removal



(9)

7a

of the solvent at reduced pressure allowed the isolation of the product **7a**. The ^{1}H and ^{13}C NMR spectra of **7a** indicated that the three arms of the trialkanolamine(3-) ligand are equivalent, consistent with a monomeric structure in solution as expected. (Although it was shown[17a] that the triethanolamine analogue of **7a** is dimeric in the solid state, it is likewise monomeric in solution.[18a])

We were unable to obtain crystals of **7a** suitable for X-ray crystallography. However, treatment of a toluene solution of **7a** with acetyl chloride (eq 10) results in the precipitation of the crystalline derivative **7b**, which was suitable for X-ray studies.

$$\underset{\textbf{7a}}{LTiO^iPr} + CH_3COCl \xrightarrow{toluene} \underset{\textbf{7b}}{LTiCl} + {}^iPrOAc \qquad (10)$$

The structure of **7b** consists of two discrete molecules packed in a non-centrosymmetric space group. An ORTEP diagram for one of the two independent molecules is shown in Figure 3, and important bond distances and angles are summarized in Table 2. As in the vanadium derivatives, the overall coordination geometry of the complex is trigonal bipyramidal. In each molecule the Cl, Ti, and N atoms lie on a pseudo 3-fold axis. The Ti–N distances of 2.255(3) and 2.266(3) Å fall at the short end of the range (2.264(3)–2.333(1) Å) found in the six other[17a,18a,b] structurally characterized titanium trialkanolamine derivatives. This confirms the presence of a Ti–N bond. Both the average Ti–O bond distance of 1.809(2) Å and the Ti–Cl distances (2.292(1) and 2.296(1) Å) are likewise consistent with those observed in related structures.

Conclusion

Homochiral trialkanolamines have several attractive features as ligands for enantioselective catalysis. (1) They are remarkably simple to synthesize in enantiopure form, especially in cases where the requisite enantiopure epoxide is available. (2) They form thermally robust tetradentate complexes with the early transition

(27) Kang, S. K.; Albright, T. A.; Eisenstein, O. *Inorg. Chem.* **1989**, *28*, 1611. Demolliens, A.; Jean, Y.; Eisenstein, O. *Organometallics* **1989**, *5*, 1457. Tatsumi, K.; Matsubura, I.; Inoue, Y.; Nakamura, A.; Miki, K.; Kasai, N. *J. Am. Chem. Soc.* **1989**, *111*, 7766.

(28) See for example: Pitchen, P.; Dunach, E.; Deshmukh, M. N.; Kagan, H. B. *J. Am. Chem. Soc.* **1984**, *106*, 8188. Suda, S.; Mukaiyama, T. *Chem. Lett.* **1991**, *431* and references therein. Burkhardt, T. J.; Funk, F. W.; Langer, A. W. *Abstracts of Papers*, 199th Meeting of the American Chemical Society, Boston, MA; American Chemical Society, Washington, DC, April 1990; INOR 600. See also ref 11 and the following: Chabardes, P. *Tetrahedron Lett.* **1988**, *29*, 6253.

(29) Nugent, W. A.; Mayer, J. M. *Metal-Ligand Multiple Bonds*; Wiley: New York, 1988; Chapter 2.

(30) Tetragonal, space group *P*4; at −50 °C, a = 18.187(2) Å, c = 11.693(5) Å, with 2350 reflections ($I > 3\sigma(I)$), R = 0.062 (Nb anisotropic, all other atoms isotropic, no hydrogens).

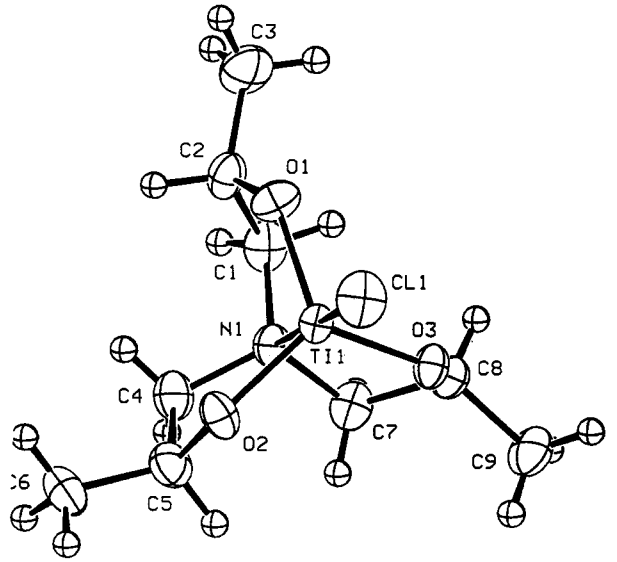


Figure 3. ORTEP drawing of one of the two independent molecules of (*S*,*S*,*S*)-**7b** showing the numbering system.

Table 2. Key Bond Distances (Å) and Angles (deg) for the Two Independent Molecules of (*S*,*S*,*S*)-**7b**

bonds	molecule 1	molecule 2
Ti–Cl	2.292(1)	2.296(1)
Ti–O(1)	1.818(2)	1.813(2)
Ti–O(2)	1.800(2)	1.803(2)
Ti–O(3)	1.815(2)	1.806(2)
Ti–N	2.266(3)	2.255(3)
O(1)–C(2)	1.425(4)	1.423(4)
O(2)–C(5)	1.430(4)	1.436(4)
O(3)–C(8)	1.425(4)	1.421(4)
Cl–Ti–O(1)	101.85(8)	101.41(8)
Cl–Ti–O(2)	103.01(8)	102.61(8)
Cl–Ti–O(3)	102.14(8)	102.57(8)
Cl–Ti–N	179.3(3)	179.1(4)
Ti–N–C(1)	106.4(2)	106.4(2)
Ti–N–C(4)	106.5(2)	106.2(2)
Ti–N–C(7)	106.2(2)	105.9(2)

metals. Discrete monomeric complexes are formed with titanium and the group 5 metals in contrast to the oligomeric species observed earlier[11] with Zr and Hf. For the case of niobium and tantalum the trialkanolamine moiety was shown to remain bound to the transition metal even under conditions where monodentate alkoxides are lost via hydrolysis. Also noteworthy in this regard is the report of Crans and co-workers on the behavior of racemic **3a**. In solvent water one arm of the trialkanolamine was displaced from vanadium, but the ligand remained bound to the metal.[20a] (3) They create a highly asymmetric environment in the vicinity of the transition metal. In many cases the coordinated ligands retain strict C_3 symmetry. The three equivalent O–C–H hydrogen atoms appear to play a significant role in imparting chirality to the coordination sphere of the metal.

Experimental Section

Reactions involving early transition metal alkoxides were run under an atmosphere of dry nitrogen in a Vacuum Atmospheres Corp. drybox. Flash chromatography was carried out on 230–400-mesh silica (EM Reagents) following the procedure of Still.[31] Gas chromatographic determinations of enantiomeric excess were carried out on a commercial Cyclodex-B capillary column (30 m × 0.25 mm i.d., 0.25-mm film).

Optical Purity of Starting Materials. Commercial (*S*)-propylene oxide (Aldrich) was converted to 1-azido-2-(trimethylsiloxy)propane[32] and analyzed by chiral GLC as described above and was found to be 98.6% ee. Similarly, commercial (*S*)-1-amino-2-propanol (Aldrich) was converted to the cyclic carbamate by treatment with carbonyldiimidazole (toluene, 60 °C). The enantiomeric excess of this material varied but was typically 91%.

(*S*,*S*,*S*)-Triisopropanolamine, (+)-3a. A mixture of (*S*)-(–)-propylene oxide (1.28 g, 22.0 mmol), (*S*)-(+)-1-amino-2-propanol (0.75 g, 10 mmol), and toluene (3 mL) was maintained in a screw-cap vial at room temperature for at least 5 days. Of roughly 30 runs following this procedure, in about a third of the cases, the product spontaneously crystallized as large transparent blocks. Alternatively, crystallization could be induced by inserting a spatula, removing it until the toluene evaporated from its surface, and then reinserting it into the solution. Rapid crystallization of the supersaturated solution ensued to provide **3a** as a white microcrystalline solid, which could be further purified by crystallization from hot toluene. Recovery was typically 1.40 g (73%), mp 102 °C (lit.[22] 96 °C); $[\alpha]^{25}_D$ +184° (*c* = 1.03, EtOH), lit.[22] $[\alpha]^{25}_D$ +136° (chloroform, 4%). ^{1}H NMR (C_6D_6): δ 1.12 (d, *J* = 7, 9H), 1.88 (dd, *J* = 2, 14), 2.25 (dd, *J* = 12, 14, 3H), 3.91 (m, 3H), 5.46 (br s, 3H). ^{13}C{^{1}H} NMR (C_6D_6): δ 20.56, 63.64, 63.96. Anal. Calcd for $C_9H_{21}NO_3$: C, 56.52; H, 11.07; N, 7.32. Found: C, 56.46; H, 10.76; N, 7.22.

In other cases it was convenient to utilize the initially formed solution containing **3a** without crystallization to prepare transition metal complexes. This was feasible because the yield of **3a** is essentially quantitative and the crude product is typically formed in 88% diastereomeric excess, as determined by ^{13}C NMR. Isomeric complexes, if formed, were easily separated via crystallization of the product.

The diastereomeric excess for (*S*,*S*,*S*)-triisopropanolamine was most efficiently determined from its ^{13}C NMR spectrum (C_6D_6) using a 10-s delay and gated decoupling during acquisition (to suppress the Overhauser effect). The resonances due to the (*R*,*S*,*S*) impurity at δ 65.14, 66.17, 66.70, and 68.02 were integrated versus the resonances due to the (*S*,*S*,*S*) isomer at δ 63.65 and 63.85. The methyl resonances were not sufficiently well resolved to be useful in this regard.

(*S*,*S*,*S*)-(+)-3a, Alternative Synthesis. (*S*)-Propylene oxide (2.32 g, 39.9 mmol) was added to a 2 M solution of ammonia in methanol (5.0 mL, 10 mmol) in a screw-cap vial. The mixture was maintained at room temperature for 24 h and was then heated for 5 days at 50 °C. Removal of solvent at reduced pressure afforded **3a** (1.86 g, 97%), mp 93 °C, $[\alpha]^{25}_D$ +173° (*c* = 1.09, EtOH). The de determined by ^{13}C NMR as described above was 94%.

(*S*)-(+)-1-Cyclohexyl-1,2-ethanediol. Following the general procedure of Riley,[25] a solution of (*S*)-(+)-hexahydromandelic acid (10.0 g, 63.2 mmol) in THF (50 mL) was added dropwise to a stirred suspension of lithium aluminum hydride (5.50 g, 145 mmol) in THF (100 mL) at 0 °C. The mixture was allowed to warm to room temperature and was heated at reflux for 2 h. The reaction was quenched by sequential dropwise addition of water (9.0 mL), 1 N NaOH (4.4 mL), and water (14 mL) and was heated to reflux for 1 h. The cooled solution was filtered. Removal of solvent at reduced pressure afforded crude diol (8.18 g, 90%), which was directly utilized in the following step.

(*S*)-(+)-Cyclohexyloxirane, 2b. A solution of (*S*)-(+)-1-cyclohexyl-1,2-ethanediol (8.08 g, 56.0 mmol) in pyridine (15 mL) was dried overnight with 3-Å molecular sieves. The solution was filtered and cooled to 0 °C, whereupon a solution of toluenesulfonyl chloride (10.68 g, 56.0 mmol) in pyridine (15 mL) was added dropwise. After 2 h the mixture was allowed to warm to room temperature and was filtered; the solids were rinsed with ether (25 mL). The solvent was removed at reduced pressure, and the residue was taken up in ether (100 mL). The ether phase was washed with 1 N HCl (50 mL), saturated $NaHCO_3$ (25 mL), and water (25 mL). The primary monotosylate was then separated from a small amount of the lower R_f regioisomer via flash chromatography (90:10 toluene/ethyl acetate). Removal of solvent afforded the primary monotosylate (10.15 g, 34.0 mmol), which was taken up in methanol and cooled to 0 °C. Sodium hydroxide (1 N, 40 mL) was added dropwise, and stirring was continued for 0.5 h. The mixture was neutralized with saturated NaH_2PO_4 (10 mL), added to water (1 L), and extracted with ether (5 × 100 mL). The combined ether extracts were washed with saturated $NaHCO_3$ and water (25 mL each) and dried ($MgSO_4$). Most of the solvent was distilled under nitrogen and then on a rotary evaporator to afford **2b** (3.97 g, 56%) as a colorless liquid. Gas chromatography indicated the presence of ether (1%) and toluene (4%). $[\alpha]^{20}_D$ = +2.1° (neat), $[\alpha]^{20}_{365}$ = +17.8° (neat); lit.[33] $[\alpha]^{20}_D$ = +0.35° (neat), $[\alpha]^{20}_{365}$ = +14.1° (neat). Spectroscopic properties were identical with those previously reported.[33]

(31) Still, W. C.; Kahn, M.; Mitra, A. J. *J. Org. Chem.* **1978**, *48*, 2923.
(32) Blandy, C.; Choukroun, R.; Gervais, D. *Tetrahedron Lett.* **1983**, *24*, 4189.
(33) Hirano, T.; Inoue, S.; Tsuruta, T. *Makromol. Chem.* **1976**, *177*, 3237.

Preparation of Ligand (+)-3b. In a screw-cap vial were placed (*S*)-(+)-1-cyclohexyloxirane (3.70 g, 95% pure, 27.9 mmol), 2.0 M ammonia in methanol solution (4.6 mL, 9.2 mmol), and methanol (5 mL). The mixture was allowed to stand overnight at room temperature and was then heated in a 50 °C oil bath for 4 days, at which time TLC showed a single spot (PMA). Removal of the solvent afforded a white residue, which was recrystallized from hot heptane to afford **3b** (3.09 g, 85%) as a white crystalline solid, mp 182–183 °C, $[\alpha]^{25}_D$ +106.2° (*c* = 0.55, methanol). ^{1}H NMR (C_6D_6): δ 1.0–1.9 (overlapping m, 30H), 2.02 (br m, 3H), 2.16 (dd, *J* = 1, 12, 3H), 2.58 (dd, *J* = 11, 12, 3H), 3.52 (m, 3H). $^{13}C\{^1H\}$ NMR (C_6D_6): δ 26.80, 26.86, 27.13, 28.96, 29.68, 42.94, 59.50, 71.53. Anal. Calcd for $C_{24}H_{45}NO_3$: C, 72.86; H, 11.47; N, 3.54. Found: C, 72.75; H, 10.98; N, 3.49.

(*R*)-3,3-Dimethyl-1,2-butanediol. Synthesis followed the published procedure of Sharpless.[26] A 1-L, three-necked, round-bottomed flask was equipped with a mechanical stirrer. The flask was charged with dihydroquinidine 9-(9′-phenanthryl) ether (0.54 g, 1.0 mmol), potassium ferricyanide (98.8 g, 300 mmol), potassium carbonate (41.46 g, 300 mmol), *tert*-butyl alcohol (176 mL), and water (176 mL). Potassium osmate-(VI) (0.08 g) was added, and the mixture was stirred for 0.5 h to give an orange suspension. The flask was immersed in a 0 °C bath and stirred for 1 h, whereupon 3,3-dimethyl-1-butene (8.42 g, 100 mmol) was added over the course of 5 h via syringe pump. The mixture was stirred at 0 °C for several more hours and then allowed to warm to room temperature overnight. Sodium sulfite (20 g) was added over the course of several minutes, and the mixture was stirred for 1 h. The mixture was rinsed into a separatory funnel with 100 mL of ether. The organic phase was separated, and the aqueous phase was extracted with ether (10 × 100 mL). Removal of solvent afforded crude diol (81% ee) containing some inorganic impurities. The ee could be directly determined by chiral capillary column gas chromatography (Cyclodex B, 120 °C). The residue was dissolved in toluene (2 mL/g diol), filtered, and cooled to −25 °C to afford crystalline material of ca. 90% ee. Repeating the crystallization process two additional times afforded diol of 99.4% ee, mp 41–42 °C, $[\alpha]^{25}_D$ = −34.4° (*c* = 5.00 methanol).

(*R*)-(−)-*tert*-Butyloxirane, 2c. A solution of toluenesulfonyl chloride (16.75 g, 87.9 mmol) in pyridine (30 mL) was added dropwise to a solution of (*R*)-3,3-dimethyl-1,2-butanediol (10.38 g, 87.8 mmol) in pyridine (20 mL) at 0 °C. The mixture was maintained at 0 °C for 8 h and was allowed to warm to room temperature overnight. The pyridine was removed at reduced pressure; the residue was taken up in ether (200 mL) and was washed with 1 N HCl (100 mL), saturated $NaHCO_3$ (50 mL), and water (50 mL). Removal of solvent afforded a residue which was azeotropically dried with dichloromethane (150 mL). This monotosylate (23.1 g, 85 mmol) was taken up in methanol (300 mL) and cooled to 0 °C. Sodium hydroxide (1 N, 90 mL, 90 mmol) was added dropwise, and stirring was continued for 0.5 h. The mixture was neutralized with saturated KH_2PO_4 (10 mL), added to water (1400 mL), and extracted into pentane (3 × 50 mL). The organic phase was washed with water (25 mL) and dried ($MgSO_4$). Pentane was distilled off using a Vigreux column. Distillation at 90–93 °C afforded **2c** (3.61 g, 41%), $[\alpha]^{25}_D$ −15.9° (*c* = 1.97, benzene), lit.[34] $[\alpha]^{25}_D$ −18.4° (*c* = 1.7, benzene), with spectroscopic properties identical to those reported in the literature.[34]

Preparation of Ligand 3c. A screw-cap vial was charged with **2c** (3.20 g, 32 mmol), 2 M ammonia in methanol solution (5.30 mL, 10.6 mmol), and methanol (2 mL). The mixture was allowed to stand overnight at room temperature and was then heated in a 50 °C oil bath for 8 days, at which time NMR analysis indicated that conversion of the starting epoxide was 92%. Removal of solvent afforded a white solid, which was thoroughly washed with toluene (10 mL), whereupon **3c** (2.78 g, 83%) could be collected as a white microcrystalline solid by filtration, mp 165–166 °C, [a]$^{25}_D$ −144.3° (*c* = 1.04, ethanol). ^{1}H NMR (C_6D_6): δ 0.98 (s, 27H), 2.27 (dd, *J* = 2, 12, 3H), 2.56 (dd, *J* = 11, 12, 3H), 3.46 (dd, *J* = 2, 11, 3H). $^{13}C\{^1H\}$ NMR (C_6D_6)L δ 26.59, 34.42, 57.31, 75.44. Anal. Calcd for $C_{18}H_{39}NO_3$: C, 68.09; H, 12.38; N, 4.41. Found: C, 67.82; H, 12.24; N, 4.31.

Preparation of Ligand (−)-3d. A screw-cap vial was charged with (*R*)-(+)-styrene oxide (5.00 g, 41.6 mmol) and 2.0 M ammonia in methanol solution (7.0 mL, 14 mmol). The mixture was allowed to stand overnight at room temperature and was then heated in a 60 °C oil bath for 5 days. After removal of solvent the residue was subjected to flash chromatography (50:45:5 toluene/EtOAc/Et_3N). Cuts 13 and 14 contained pure **3d** (0.92 g, 18%) as a white powder, while cuts 15 and 16 contained additional impure **3d** (1.18 g), which was rechromatographed with a subsequent batch of ligand. Alternatively, the crude product could be freed of isomeric impurities by crystallization from hot 1:1 heptane/toluene. This procedure afforded fine white needles of **3d**, mp 142–143 °C, $[\alpha]^{25}_D$ −95.5° (*c* = 1.02, ethanol). ^{1}H NMR (C_6D_6): δ 2.32 (dd, *J* = 2, 12, 3H), 2.82 (dd, *J* = 10, 12, 3H), 4.96 (dd, *J* = 2, 10, 3H), 4.48 (br s, 3H), 7.05–7.25 (m, 9H), 7.40 (d, *J* = 8, 6H). $^{13}C\{^1H\}$ NMR ($CDCl_3$): δ 63.36, 70.91, 125.92, 127.72, 128.49, 141.88. Anal. Calcd for $C_{24}H_{27}O_3N$: C, 76.36; H, 7.21; N, 3.71. Found: C, 76.06; H, 7.26; N, 3.54.

Vanadium Complex 4a. A solution of **3a** (10 mmol) in ether (10 mL) was added dropwise to a solution of tri-*n*-propyl vanadate (2.91 g, 12.0 mmol) in ether (20 mL). The pale yellow precipitate that formed was collected by filtration, washed with ether, and dried in high vacuum to afford **4a** (2.29 g, 90%) as a white crystalline solid. ^{1}H NMR ($CDCl_3$): δ 1.20 (d, *J* = 7, 9H), 2.64 (dd, *J* = 12, 13, 3H), 3.05 (dd, *J* = 4, 13, 3H), 4.96 (m, 3H). $^{13}C\{^1H\}$ NMR ($CDCl_3$): δ 20.57, 61.17, 80.74. Anal. Calcd for $C_9H_{18}NO_4V$: C, 42.36; H, 7.11; N, 5.49. Found: C, 42.12; H, 7.04; N, 5.14.

Vanadium Complex 4b. To a flask containing tri-*n*-propyl vanadate (0.24 g, 1.0 mmol) and ligand **3b** (0.39 g, 1.0 mmol) was added THF (10 mL), and the mixture was stirred for 1 h. Filtration and drying in high vacuum afforded **4b** (0.30 g, 65%) as a white solid. Additional product was collected upon cooling the supernatant to −25 °C, mp >200 °C. ^{1}H NMR ($CDCl_3$): δ 0.9–2.0 (m, 33H), 2.94 (app t, *J* = 13, 3H), 3.01 (dd, *J* = 5, 13, 3H), 4.50 (m, 3H). $^{13}C\{^1H\}$ NMR ($CDCl_3$): δ 25.96, 26.10, 26.43, 28.83, 29.03, 43.51, 57.77, 89.00. Anal. Calcd for $C_{24}H_{42}NO_4V$: C, 62.73; H, 9.21; N, 3.05. Found: C, 62.59; H, 8.92; N, 3.04.

Vanadium Complex 4c. A solution of **3c** (0.32 g, 1.0 mmol) in ether (5 mL) was added to a solution of tri-*n*-propyl vanadate (0.24 g, 1.0 mmol) in toluene (5 mL). The precipitate was collected by filtration and dried in high vacuum to afford **7c** (0.24 g, 63%) as a white solid. ^{1}H NMR ($CDCl_3$): δ 0.90 (s, 27H), 2.82 (app t, *J* = 12, 3H), 3.00 (dd, *J* = 4, 12, 3H), 4.42 (dd, *J* = 4, 12, 3H). $^{13}C\{^1H\}$ NMR ($CDCl_3$): δ 26.06, 35.62, 56.14, 92.59. Anal. Calcd for $C_{18}H_{36}NO_4V$: C, 56.68; H, 9.51; N, 3.67. Found: C, 56.76; H, 9.40; N, 3.38.

Vanadium Complex 4d. To a solution of **3d** (0.31 g, 0.82 mmol) in THF (5.0 mL) was added a solution of tri-*n*-propyl vanadate (0.24 g, 1.0 mmol) in THF (5 mL). The precipitate was collected by filtration, and the last traces of solvent were removed in vacuum to afford **4d** (0.31 g, 86%), mp >200 °C. ^{1}H NMR ($CDCl_3$): δ 3.12 (app t, *J* = 13, 3H), 3.42 (dd, *J* = 5, 13), 5.91 (dd, *J* = 5, 13), 7.28-7.45 (m, 15H). $^{13}C\{^1H\}$ NMR ($CDCl_3$): δ 61.76, 86.03, 125.47, 128.22, 128.67, 140.48. Anal. Calcd for $C_{24}H_{24}NO_4V$: C, 65.31; H, 5.48; N, 3.17. Found: C, 65.44; H, 5.21; N, 2.99.

Niobium Complex 5a. Niobium(V) ethoxide (0.96 g, 3.0 mmol Nb) was dissolved in THF (10 mL). A solution of (*S*,*S*,*S*)-**3a** (0.57 g, 3.0 mmol) in THF (10 mL) was added over the course of several minutes, and the mixture was allowed to stand for 30 min. The solvent was removed at reduced pressure to afford **5a** as a colorless liquid (1.08 g, 97%). ^{1}H NMR ($CDCl_3$): δ 1.22 (d, *J* = 7, 9H), 1.27 (t, *J* = 7, 6H), 2.84 (dd, *J* = 11, 12, 3H), 3.04 (dd, *J* = 5, 12, 3H), 4.40 (q, *J* = 7, 4H), 4.78 (m, 3H). $^{13}C\{^1H\}$ NMR ($CDCl_3$): δ 18.81, 21.18, 67.67, 68.92, 75.39. Anal. Calcd for $C_{13}H_{28}NO_5Nb$: C, 42.06; H, 7.60; N, 3.77. Found: C, 41.96; H, 7.25; N, 3.38.

Tantalum Complex 5b. The above procedure was followed substituting tantalum(V) ethoxide (1.22 g, 3.00 mmol Ta) as starting alkoxide. The product is initially a waxy solid due to evaporative cooling but melts to a colorless liquid (1.33 g, 96%) upon warming to room temperature. ^{1}H NMR ($CDCl_3$): δ 1.12 (d, *J* = 7, 9H), 1.16 (t, *J* = 7, 6H), 2.82 (dd, *J* = 10, 11, 3H), 3.07 (dd, *J* = 5, 11), 4.46 (q, *J* = 7, 4H), 4.76 (m, 3H). $^{13}C\{^1H\}$ NMR ($CDCl_3$): δ 19.15, 21.85, 67.57, 67.86, 73.91. Anal. Calcd for $C_{13}H_{28}NO_5Ta$: C, 33.99; H, 6.14; N, 3.05. Found: C, 33.84; H, 6.09; N, 2.78.

Tetrakis(μ-oxoniobium) Tetramer 6a. Water (54 mL, 3.0 mmol) was added over the course of 1 min to a solution of **5a** (3 mmol), prepared as above, in THF (10 mL). The mixture was allowed to stand for 1 h, whereupon the solvent was removed at reduced pressure. Hexane (5 mL) was added to aid in removal of the last traces of THF. The residue was dissolved in 20 mL of hot toluene, which upon cooling afforded **6a** as the toluene solvate, a single large transparent crystal. Crushing this material and pumping in high vacuum afforded solvent-free **6a** (0.52 g, 59%) as a white powder. ^{1}H NMR ($CDCl_3$): δ 1.04 (d, *J* = 6, 6H), 1.14 (d, *J* = 6, 6H), 1.45 (d, *J* = 6, 6H), 2.52 (2 overlapping dd, 4H), 2.86 (2 overlapping dd, 4H), 3.27 (dd, *J* = 6, 13, 2H), 3.46 (app t, *J* = 10, 2H), 4.46 (m, 2H), 4.71 (m, 2H), 5.61 (m, 2H). $^{13}C\{^1H\}$ NMR

(34) Chadha, A.; Goergens, U.; Schneider, M. P. *Tetrahedron: Asymmetry* **1993**, *4*, 1449 and references therein.

($CDCl_3$): δ 20.18, 20.38, 21.98, 63.83, 66.63, 66.95, 74.17, 75.80, 77.09. Anal. Calcd for $C_{18}H_{36}N_2O_8Nb_2$: C, 36.38; H, 6.11; N, 4.71. Found: C, 36.06; H, 6.24; N, 4.47.

Tetrakis(μ-oxotantalum Tetramer 6b. The above procedure was followed substituting **5b** as the starting alkoxide, yielding **6b** (0.64 g, 55%) as a white solid. ^1H NMR ($CDCl_3$): δ 1.04 (d, J = 7, 6H), 1.15 (d, J = 7, 6H), 1.44 (d, J = 7, 6H), 2.50 (dd, J = 11, 13, 2H), 2.61 (dd, J = 4, 13, 2H), 2.86 (2 overlapping dd, 4H), 3.28 (2 overlapping dd, 4H), 4.48 (m, 2H), 4.80 (m, 2H), 5.49 (m, 2H). $^{13}C\{^1H\}$ NMR ($CDCl_3$): δ 20.49, 21.23, 23.00, 64.51, 67.19, 67.82, 72.74, 74.55, 75.92. Anal. Calcd for $C_{18}H_{36}N_2O_8Ta_2$: C, 28.06; H, 4.71; N, 3.64. Found: C, 28.40; H, 4.92; N, 3.38.

Titanium Complex 7a. A solution of **3a** (10 mmol) in ether (10 mL) was added to a solution of titanium(IV) isopropoxide (2.84 g, 10.0 mmol) in toluene (10 mL). Removal of the solvent afforded **7a** (2.83 g, 96%) as a white solid. A 0.5-g portion of this material was dissolved in hexane (10 mL) and cooled to −25 °C to afford crystals of the product as thin colorless prisms. ^1H NMR ($CDCl_3$): δ 1.10 (d, J = 7, 9H), 1.32 (d, J = 7, 6H), 2.83–2.96 (m, 6H), 4.63 (septet, J = 7, 1H), 4.90 (m, 3H). $^{13}C\{^1H\}$ NMR ($CDCl_3$): δ 21.23, 25.72, 63.50, 75.65, 76.32. Anal. Calcd for $C_{12}H_{25}NO_4Ti$: C, 48.82; H, 8.54; N, 4.74. Found: C, 48.40; H, 8.16; N, 4.75.

Titanium Complex 7b. Crude **7a** (2.80 g, 9.48 mmol) prepared as above was dissolved in toluene (30 mL), and acetyl chloride (1.00 g, 12.7 mmol) was added. Over the course of several days a precipitate gradually formed. White microcrystals were manually separated from several brown particles which formed to afford after drying in high vacuum **7b** (0.78 g, 30%). ^1H NMR ($CDCl_3$): δ 1.17 (d, J = 7, 9H), 3.03–3.18 (m, 6H), 5.26 (m, 3H). $^{13}C\{^1H\}$ NMR ($CDCl_3$): δ 20.55, 65.00, 80.20. Anal. Calcd for $C_9H_{18}ClNO_3Ti$: C, 39.80; H, 6.68; N, 5.16. Found: C, 39.74; H, 6.21; N, 4.94.

X-ray Crystallographic Study of Complexes 4c and 7b. The crystallographic investigations of **4c** were carried out on an Enraf–Nonius CAD4 diffractometer, while that of **7b** was carried out on a Syntex P3 diffractometer. Both instruments (graphite monochromator; Mo Kα radiation; λ = 0.71069 Å) were equipped with a low-temperature apparatus. The crystal system, space group, and approximate unit cell dimensions were determined during preliminary investigations. The quality of both crystals was found to be adequate on the basis of ω scans, which showed the peak height at half-width to be ca. 0.33° ω for **4c** and 0.24° ω for **7b**. The unit cell parameters were refined from the Bragg angles of 25 (**4c**) or 45 (**7b**) computer-centered reflections. Intensity data were collected using the ω scan technique. The intensities of standard reflections were monitored periodically, but only statistical variations were noted over the course of each data collection. Azimuthal scans showed little variation in intensity with ψ. No correction for absorption was made. Both structures were solved by direct methods. The refinement and analysis of the two structures were carried out using a package of local programs.[35] The atomic scattering factors were taken from the tabulations of Cromer and Waber; anomalous dispersion corrections for Ti, Cl, and V were taken from Cromer.[36] In the full-matrix least-squares refinement, the function minimized was $\Sigma w(|F_o| - |F_c|)^2$ with weights, w, assigned as $[\sigma^2(I) + 0.0009I^2]^{-1/2}$.

Crystal Data for 4c. Suitable crystals were obtained by slow evaporation of an ether/toluene solution. Crystal data for $VO_4NC_{18}H_{36}$: colorless plate, ~0.26 × 0.16 × 0.36 mm, monoclinic, $P2_1$ (no. 4), a = 10.098(3) Å, b = 11.581(3) Å, c = 10.155(2) Å, β = 117.67(2)°, T = −100 °C, V = 1051.8 Å^3, Z = 2, fw = 381.43, D_c = 1.204 g/cm^3, μ(Mo) = 4.74 cm^{-1}. A total of 2813 data were collected (scan width = 1.20° ω, variable scan speed = 3.90–11.70 min^{-1}, 4.5° < 2θ < 56.0°). All non-hydrogen atoms were refined with anisotropic thermal parameters. Initially, an attempt was made to refine the hydrogen atoms; one C–H bond became rather long at 1.12 Å and one rather short at 0.81 Å. Therefore, hydrogen atoms were included as fixed contributions with an idealized C–H distance of 0.95 Å and assigned thermal parameters 1.0 greater than B_{iso}(carbon). The refinement of 216 parameters using 2310 reflections with $I > 2.5\sigma(I)$ converged at R = 0.032 and R_w = 0.037. The largest peak in the residual density was 0.28 e Å^{-3} and was located near O11. The (*R*,*R*,*R*) configuration for ligand **3c** is confirmed; the enantiomorphic structure converged to R values which are approximately 0.0025 higher.

Structural Details for 7b. Suitable crystals were obtained by slow evaporation of a 1,2-dichloroethane solution. Crystal data for $TiClO_3NC_9H_{18}$: colorless, irregular block, ~0.38 × 0.34 × 0.45 mm, orthorhombic, $P2_12_12_1$ (no. 19), a = 13.421(3) Å, b = 13.716(2) Å, c = 13.878(2) Å, T = −70 °C, V = 2554.7 Å^3, Z = 8, fw = 271.60, D_c = 1.412 g/cm^3, μ(Mo) = 8.62 cm^{-1}. A total of 3303 data were collected (scan width = 1.50–2.20° ω, variable scan speed = 2.00–5.00 min^{-1}, 2.9° < 2θ < 55.0°). All non-hydrogen atoms were refined with anisotropic thermal parameters; hydrogen atoms were refined isotropically. The refinement of 415 parameters using 2587 reflections with $I > 3\sigma(I)$ converged at R = 0.027 and R_w = 0.029. The largest peak in the residual density was 0.19 e Å^{-3} and was located near H11′.

The structure consists of two discrete molecules packed in a noncentrosymmetric space group. The two independent molecules are related by a pseudotranslation of 0.5 along the c axis. The reflections with I odd were thus systematically weak; however, most of them were "observed" and the refinement of the structure proceeded smoothly (the highest correlation coefficient being 0.40).

The bond distances and angles for all chemically equivalent bonds agree with each other very well. The (*S*,*S*,*S*) configuration for ligand **3a** is confirmed; the enantiomorphic structure converged at R = 0.036 and R_w = 0.041.

Acknowledgment. The authors thank Professors Odile Eisenstein, John Verkade, K. Barry Sharpless, and Debbie C. Crans for helpful discussions.

Supplementary Material Available: Tables of atomic coordinates, anisotropic thermal parameters, and complete interatomic distances and angles for compounds **4c** and **7b** (7 pages); structure factor amplitudes (13 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

(35) Calabrese, J. C. 1991, Central Research and Development, DuPont Co., P.O. Box 80228, Wilmington, DE 19880-0228.

(36) *International Tables for X-ray Crystallography*; Kynoch Press: Birmingham, England, 1974; Vol. IV, (a) Table 2.2B, (b) Table 2.3.1.