during Berry pseudorotation, but due to the more rigid ring system for **2**, a higher barrier exists in executing this process compared to **4**.

Conclusion

The principal conclusion of the work presented here is that six-membered rings of oxyphosphoranes, like that previously known for five-membered ring derivatives, have an apical-equatorial site preference in a trigonal bipyramid. The preferred ring conformation of saturated six-membered rings is that of a boat. The apical-equatorial site preference also seems to apply to phosphoranes with seven-membered and eight-membered rings. These results support the recent NMR studies of Yu and Bentrude[53] indicating that nonchair (boat and/or twist) conformations are the normal conformations for six-membered rings in oxyphosphoranes and that these conformations for intermediates in enzymatic reactions of nucleoside 3',5'-monophosphates should receive serious consideration. Our study also lends credence to the theoretical investigation by van Ool and Buck[9] who conclude that hydrolysis of cAMP with phosphodiesterase proceeding by way of trigonal-bipyramidal intermediate D (see Introduction) must have the intermediate with an apical-equatorial ring orientation.

The solution state structure of phosphorinane C, closely related to the cis-annelated furanose ring system in **7**, has been suggested[16] to be trigonal bipyramidal with a diequatorially oriented ring. This conclusion bears further scrutiny in view of the uniform apical-equatorial disposition of phosphorinane rings found in the present study.[54]

We may anticipate that additional studies focusing on six-membered ring systems in oxyphosphoranes and related analogues will yield further insight that should prove useful in constructing mechanistic pathways for enzymatic and nonenzymatic nucleophilic displacement reactions of phosphorus.

Acknowledgment. The support of this research by the National Science Foundation (Grant CHE88-19152 and the Army Research Office is gratefully acknowledged.

Supplementary Material Available: Tables of thermal parameters, additional bond lengths and angles, hydrogen atom parameters (Tables S1-S3 for **1**, Tables S4-S6 for **2**, Tables S7-S9 for **3**, and Tables S10-S12 for **4**), and atomic coordinates (Tables S13-S16 for **1-4**, respectively) (39 pages). Ordering information is given on any current masthead page.

(53) Yu, J. H.; Bentrude, W. G. *J. Am. Chem. Soc.* **1988**, *110*, 7897. Ibid. *Tetrahedron Lett.* **1989**, *30*, 2195.

(54) Holmes, R. R.; Kumara Swamy, K. C.; Holmes, J. M.; Day, R. O., submitted for publication.

Communications to the Editor

Molecular Recognition of Ethers with Modified Organoaluminum Reagents

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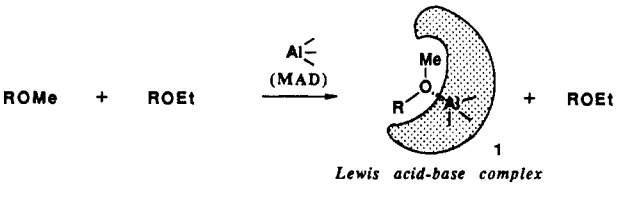
The chemistry of molecular recognition is a subject of current interest, and a number of recognition systems capable of reversible binding interactions have been developed for this purpose.[1-4] Most of these artificial enzymes utilize effective hydrogen-bonding interactions between substrate and receptor as also seen in natural enzymes. With organic substrates of weak hydrogen-bonding capability such as ethers, however, such tight binding behavior cannot be expected. Here we introduce exceptionally bulky, oxygenophilic methylaluminum bis(2,6-di-*tert*-butyl-4-methylphenoxide) (MAD) featuring a Lewis acidic molecular cleft for recognition of structurally or electronically similar ether substrates based on selective Lewis acid-base complex formation.[5]

Table I. Recognition Ability of Various Lewis Acids with Two Different Ethers[a]

Lewis acid	complexatn ratio:[b] $Ph(CH_2)_3OMe$ + $Ph(CH_2)_3OEt$
MAD	100:0
methylaluminum bis(2,6-diisopropylphenoxide)	*c*
i-Bu_3Al	4:1
$SnCl_4$	*d*
BEt_3	*c*
$BF_3{\cdot}OEt_2$	5:3

Lewis acid	complexatn ratio:[b] $CH_3CH_2CH_2OMe$ + EtOEt
MAD	96:4
$BF_3{\cdot}OEt_2$	3:2

[a] Two different ethers (1 mmol each) were mixed with 1 equiv of Lewis acid in $CDCl_3$ or CD_2Cl_2 (2 M solution) in a 5-mm NMR tube at 20-25 °C, and the 125-MHz ^{13}C NMR spectra were taken at -50 to -100 °C. [b] The complexation ratio was determined by low-temperature ^{13}C NMR analysis of ethereal α-carbons. [c] No complexation was observed. See also text. [d] Two equivalents of ethers coordinated to $SnCl_4$ to give a 2:1 complex.



Lewis acid-base complex

(1) Polyethers as host: (a) Cram, D. J. *Science (Washington, D.C.)* **1983**, *219*, 1177. (b) Lehn, J.-M. *Ibid.* **1985**, *227*, 849. (c) Lehn, J.-M. *Angew. Chem., Int. Ed. Engl.* **1988**, *27*, 89. (d) Cram, D. J. *Ibid.* **1988**, *27*, 1009.

(2) Cyclodextrins as host: (a) Bender, M. L.; Komiyama, M. *Cyclodextrin Chemistry*; Springer-Verlag: New York, 1978. (b) Saenger, W. *Angew. Chem., Int. Ed. Engl.* **1980**, *19*, 344. (c) D'Souza, V. T.; Bender, M. L. *Acc. Chem. Res.* **1987**, *20*, 146.

(3) Cyclophanes as host: (a) Stetter, H.; Roos, E.-E. *Chem. Ber.* **1955**, *88*, 1390, 1395. (b) Odashima, K.; Itai, A.; Iitaka, Y.; Koga, K. *J. Am. Chem. Soc.* **1980**, *102*, 2504. (c) Miller, S. P.; Whitlock, H. W., Jr. *Ibid.* **1984**, *106*, 1492. (d) Winkler, J.; Coutouli-Argyropoulou, E.; Leppkes, R.; Breslow, R. *Ibid.* **1983**, *105*, 7198. (e) Diederich, F.; Griebel, D. *Ibid.* **1984**, *106*, 8037. (f) Schneider, H.-J.; Blatter, T. *Angew. Chem., Int. Ed. Engl.* **1988**, *27*, 1163. (g) Collet, A. *Tetrahedron* **1987**, *43*, 5725.

(4) Molecular clefts as receptors: (a) Rebek, J., Jr.; Marshall, L.; Wolak, R.; Parris, K.; Killoran, M.; Askew, B.; Nemeth, D.; Islam, N. *J. Am. Chem. Soc.* **1985**, *107*, 7476. (b) Rebek, J., Jr.; Askew, B.; Islam, N.; Killoran, M.; Nemeth, D.; Wolak, R. *Ibid.* **1985**, *107*, 6736. (c) Rebek, J., Jr. *Chemtracts: Org. Chem.* **1989**, *2*, 337. (d) Rebek, J., Jr. *Angew. Chem., Int. Ed. Engl.* **1990**, *29*, 245.

(5) For synthetic applications of MAD, see: Maruoka, K.; Itoh, T.; Sakurai, M.; Nonoshita, K.; Yamamoto, H. *J. Am. Chem. Soc.* **1988**, *110*, 3588.

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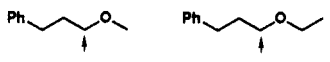
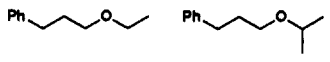
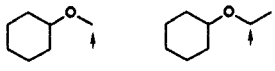
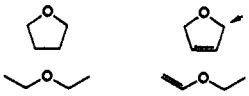
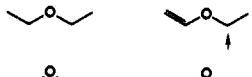
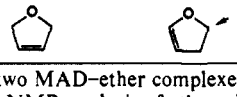
Table II. Selective Complexation of Two Different Ethers with MAD

entry	ethers	complexatn ratio[a]
1		100:0
2		100:0
3		96:4
4		100:0[b]
5		81:19[c]
6		100:0
7		90:10
8		100:0[b]
9		100:0

[a] The ratio of two MAD–ether complexes was determined in $CDCl_3$ at −50 °C by ^{13}C NMR analysis of ethereal α-carbons at the indicated arrows. [b] At −90 °C in CD_2Cl_2. [c] Determined on the basis of the phenoxy carbons as well as ethereal α-carbons.

We have examined the recognition ability of MAD with two different ether substrates by low-temperature ^{13}C NMR spectroscopy. For example, the 125-MHz ^{13}C NMR measurement of a mixture of 1 equiv each of MAD, methyl 3-phenylpropyl ether, and ethyl 3-phenylpropyl ether in $CDCl_3$ (0.4 M solution) at −50 °C showed that the original signal of methyl ether at δ 58.66 shifted downfield to δ 60.09, whereas the signal of the α-methylene carbon of ethyl ether remained unchanged. This result showed the virtually complete recognition between methyl and ethyl ethers with MAD giving Lewis acid–base complex **1** (R = $(CH_2)_3Ph$) exclusively. It should be noted that this remarkable selectivity can only be achieved with exceptionally bulky organoaluminum reagents as ascertained by comparison with other Lewis acids (Table I). The use of two exceptionally bulky 2,6-di-*tert*-butyl-4-methylphenoxy ligands in MAD is essential for providing one recognition site with the complementary size, shape, and coordination capacity. Furthermore, MAD exists as a monomeric species in solution,[6] thereby exhibiting a high oxygenophilic character even with weak Lewis bases. In contrast, less bulky methylaluminum bis(2,6-diisopropylphenoxide) and methylaluminum bis(2,4,6-trimethylphenoxide) were found not to form any coordination complexes with ethers at low temperature, probably due to their strong self-association through electron-deficient bonds. Other examples of selective complexation of two different ethers with MAD are listed in Table II. Ethers possessing sterically less hindered alkyl substituents form coordination complexes more easily than their bulky counterparts (entries 1–6). The more basic ethereal oxygens coordinate more strongly to MAD than the less basic oxygens (entries 7–9).

The ready availability of various types of hindered polyphenols enables the molecular designing of various polymeric organoaluminum reagents, implying the widespread potential of this molecular recognition chemistry. For example, this chemistry allows the realization of a complexation chromatography, i.e., separation of heteroatom-containing solutes by complexation with stationary, insolubilized organoaluminum reagents.[7] Accordingly, treatment of sterically hindered triphenol **2**[8] (2 mmol) in CH_2Cl_2

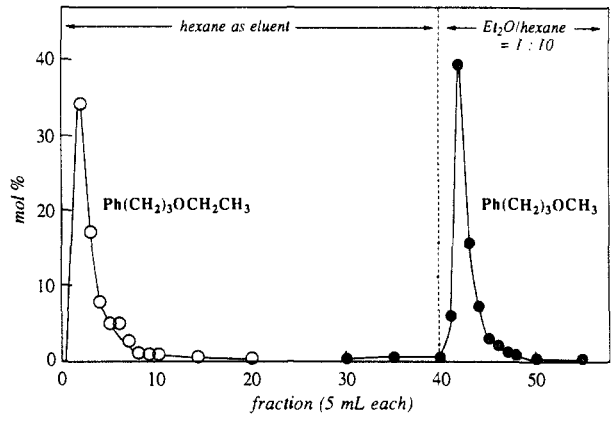
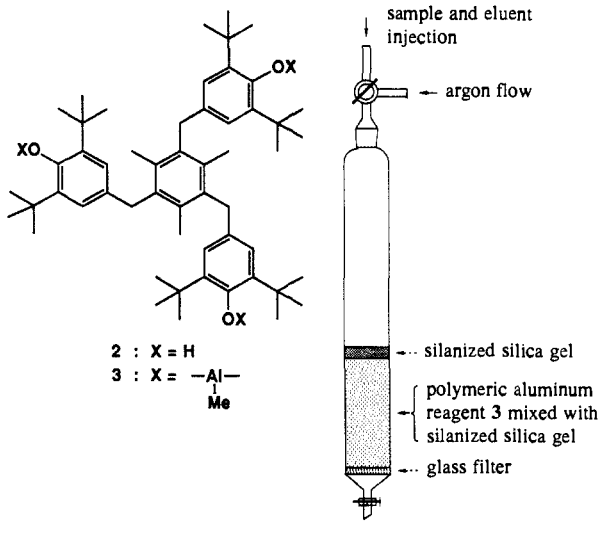


Figure 1. Separation of methyl 3-phenylpropyl ether (shaded circles) and ethyl 3-phenylpropyl ether (open circles) by complexation chromatography.

with Me_3Al (3 mmol) at room temperature for 1 h gave rise to the polymeric monomethylaluminum reagent **3**. After evaporation



of solvent, the residual solid was ground to a powder and mixed with silanized silica gel (1.7 g) in an argon box.[9] This was packed in a short-path glass column (10 mm i.d. × 150 mm) as a stationary phase and washed once with dry, degassed hexane to remove unreacted free triphenol **2**. Then a solution of methyl 3-phenylpropyl ether and ethyl 3-phenylpropyl ether (0.5 mmol each) in degassed hexane was charged on this short-path column. As shown in Figure 1, this technique allows the surprisingly clean separation of structurally similar ether substrates.[10] Ethyl 3-phenylpropyl ether and isopropyl 3-phenylpropyl ether or the THF and THP ethers of 4-(*tert*-butyldiphenylsiloxy)-1-butanol can be separated equally well with this short-path column chromatography.[11] The latter case would demonstrate an effective way to purify structurally or electronically similar ethers in the segment synthesis of polyether antibiotics. With these examples at hand, it appears feasible to separate the wide range of ethers listed in Table II by complexation chromatography. Although a variety of complexation chromatographies have been advanced,[12] the use, as a stationary phase, of exceptionally bulky aluminum reagents, which possess exceedingly high recognition ability, is crucial in effecting the clean separation of structurally and/or electronically similar organic substrates.

(6) Strarowieyski, K. B.; Pasynkiewicz, S.; Skowronska-Ptasinska, M. *J. Organomet. Chem.* **1975**, *90*, C43.
(7) Deyl, Z.; Macek, K.; Janak, J. *Liquid Column Chromatography—A Survey of Modern Techniques and Applications*; Elsevier: Amsterdam, 1975.
(8) Kindly provided by Adeka Argus Chemical Co., Ltd.
(9) Silanized silica gel was dried at 60–80 °C for 1 h under vacuum before use. Mixing of the polymeric organoaluminum reagent **3** with silanized silica gel (weight ratio = 1:1) is recommended for obtaining efficient separation and reproducibility in column chromatography.
(10) It should be noted that the separation of methyl 3-phenylpropyl ether and its ethyl analogue cannot be readily accomplished by ordinary silica gel chromatography.
(11) For details, see supplementary material.
(12) Schurig, V. *Angew. Chem., Int. Ed. Engl.* **1984**, *23*, 747.

Acknowledgment. This research was supported by the Kurata Foundation.

Supplementary Material Available: Characteristic ^{13}C NMR data for free ethers and their complexes with MAD and experimental details and figures for complexation chromatography (6 pages). Ordering information is given on any current masthead page.

Generation and Trapping of 1,5-Dehydroquadricyclane

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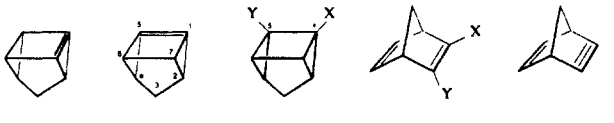
Several years ago evidence was provided for the existence of 1,7-dehydroquadricyclane (**1**) as a reactive intermediate.[1-3] **1** was generated by treatment of **3f** with lithium 2,2,6,6-tetramethylpiperidide in the presence of anthracene, 2,5-dimethylfuran, or trimethylisoindole and trapped as a Diels-Alder adduct. Under these reaction conditions, no indications were obtained for the formation of 1,5-dehydroquadricyclane (**2**), whereas the reaction of **3f** with *n*-butyllithium proceeded via **1** as the major and **2** as the minor intermediate.[1,2] We now report on the controlled generation of **2** and on some trapping experiments of this highly strained pyramidalized bridgehead olefin.

Schlosser[4] and Brandsma[5] have shown independently that norbornadiene **4a** can be metalated at the vinylic position to give **4b** (or **4c/d**) by the mixture of *n*-butyllithium (BuLi) and sodium *tert*-butoxide or potassium *tert*-butoxide in tetrahydrofuran at −78 °C. We have used this reaction and converted **4d** with 1,2-dibromoethane into 2-bromonorbornadiene **4e**[6] in 40% yield and with 4-toluenesulfonyl chloride into 2-chloronorbornadiene **4f**[6] in 34% yield.



1 **2** **3** **4** **5**

3, 4	a	b	c	d	e	f	g	h	i	j	k	l
X	H	Li	Na	K	Br	Cl	Br	Cl	Br	Br	Br	Br
Y	H	H	H	H	H	H	Cl	Li	Li	K	Br	$SiMe_3$

With respect to **4a**, the acidity of C-3 in **4e** and **4f** should be enhanced by the vicinal halide. Indeed, treatment of **4f** with *tert*-butyllithium (*t*-BuLi) in THF/pentane at −78 °C for 45 min produced a yellow precipitate. Addition of 1,2-dibromoethane to the stirred suspension, warming to room temperature, and aqueous workup afforded a 44% yield of 2-bromo-3-chloronorbornadiene **4g**.[7,8] The ^{13}C NMR spectrum of the precipitate in THF-d_8 was consistent with 2-chloro-3-lithionorbornadiene **4h** [58.22 (d), 60.28 (d), 72.18 (t), 139.91 (d), 144.45 (d), 159.47 (s), 178.55 (s)]. Mixtures of **4h** in THF were stable at room temperature, but decomposed in boiling THF in the presence of 2,5-dimethylfuran to a black solution, from which **4f** was isolated as the sole product. No evidence was observed for the formation of norbornenyne **5**.[9]

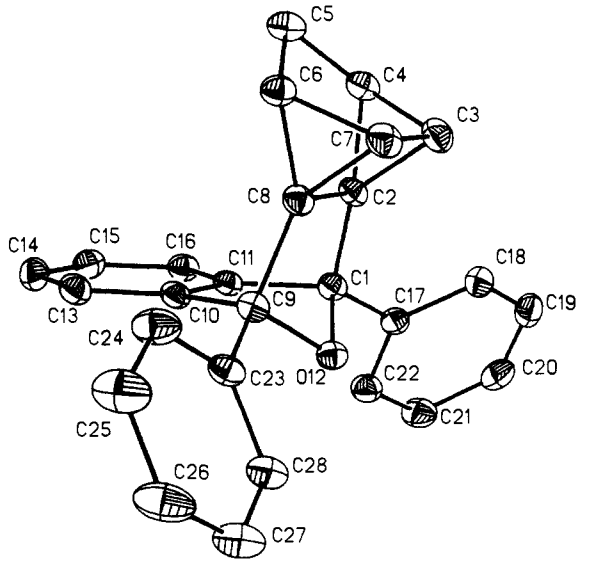


Figure 1. ORTEP view of **6a**. The thermal ellipsoids are drawn at the 20% probability level. Hydrogens were omitted for clarity. Selected interatomic distances are as follows (Å): C1-O12, 1.481 (3); C1-C2, 1.519 (4); C1-C11, 1.520 (5); C1-C17, 1.500 (4); C2-C3, 1.516 (5); C2-C4, 1.492 (4); C2-C8, 1.546 (4); C3-C4, 1.529 (5); C3-C7, 1.536 (4); C4-C5, 1.517 (4).

Fast lithium-bromine exchange excluded the use of *t*-BuLi as a base for the lithiation of **4e** to give **4i**. **4j** was obtained by reaction of **4d** with the bromide **4e** in THF at −65 to −55 °C for 2 h. Addition of 1,2-dibromoethane to the suspension of **4j** afforded a 65% yield of **4k**. The reaction sequence allows a one-pot synthesis of **4k** starting from **4a** without isolation of **4e**: After metalation of norbornadiene with BuLi/KO-*t*-Bu in THF at −105 to −35 °C, 0.50 equiv of 1,2-dibromoethane was added and the mixture kept at −35 °C for 1 h. Addition of the remaining 0.50 equiv of dibromoethane at −35 °C, warming to room temperature, and aqueous workup gave rise to a 53% yield of **4k**.[8,10]

Conversion of **4g** and **4k** into the quadricyclanes **3g**[11] and **3k**[8,12] was achieved in yields of 66 and 77% by irradiating 0.40 M solutions of the norbornadienes in ether at room temperature with a 150-W mercury high-pressure lamp in a glass apparatus in the presence of 5 mol % of acetophenone.

When a solution of **3k** in THF/pentane at −78 °C was treated with 2.0 equiv of *t*-BuLi and the mixture kept at this temperature for 1 h, addition of chlorotrimethylsilane led to bromosilane **3l** in 60% yield. This result indicates that **3i** was formed by lithium-bromine exchange, but that at −78 °C LiBr elimination to give **2** did not take place. However, when the cooled solution (−78 °C) of **3i** was transferred by syringe to a solution of diphenylisobenzofuran in THF and the mixture was allowed to warm to 20 °C and kept at this temperature for 30 min, aqueous workup and removal of excess diene with maleic anhydride[13] afforded a 40% yield of an 84:16 mixture of **6a**[8,14] and **7a**.[8,15] **7a** was less

(1) Harnisch, J.; Baumgärtel, O.; Szeimies, G.; Van Meerssche, M.; Germain, G.; Declercq, J.-P. *J. Am. Chem. Soc.* **1979**, *101*, 3370.
(2) Baumgärtel, O.; Szeimies, G. *Chem. Ber.* **1983**, *116*, 2180.
(3) Baumgärtel, O.; Harnisch, J.; Szeimies, G.; Van Meerssche, M.; Germain, G.; Declercq, J.-P. *Chem. Ber.* **1983**, *116*, 2205.
(4) Stähle, M.; Lehmann, R.; Kramař, J.; Schlosser, M. *Chimia* **1985**, *39*, 229.
(5) Verkruijsse, H. D.; Brandsma, L. *Recl. Trav. Chim. Pays-Bas* **1986**, *105*, 66.
(6) **4e** and **4f** are known compounds: see ref 2. For **4f**, see also: Davies, D. I. *J. Chem. Soc.* **1960**, 3669.
(7) **4g**: bp 74-77 °C/12 Torr; ^{13}C NMR ($CDCl_3$) δ 56.88 (d), 57.88 (d), 71.42 (t), 128.24 (s), 140.99 (d), 141.57 (d), 143.93 (s).
(8) Further spectral data are available as supplementary material.
(9) The intermediacy of 2-norbornyne has been established: Gassman, P. G.; Gennick, I. *J. Am. Chem. Soc.* **1980**, *102*, 6864.
(10) **4k**: bp 85-86 °C/12 Torr; ^{13}C NMR ($CDCl_3$) δ 58.52 (d), 71.84 (t), 132.91 (s), 141.09 (d).
(11) **3g**: bp 20 °C/0.01 Torr; ^{13}C NMR ($CDCl_3$) δ 24.17 (d), 24.93 (d), 30.68 (t), 34.38 (d), 35.17 (d), 39.07 (s), 49.80 (s).
(12) **3k**: bp 25 °C/0.01 Torr; ^{13}C NMR ($CDCl_3$) δ 24.84 (d), 30.93 (t), 35.04 (d), 39.19 (s); HRMS calcd for $C_7H_9{}^{79}Br^{81}Br$ 249.881, found 249.876.
(13) Wittig, G. *Organic Syntheses*; Wiley: New York, 1963; Collect. Vol. IV, p 964.
(14) **6a**: mp 151-153 °C; ^{13}C NMR ($CDCl_3$) δ 15.45 (d, C-3, C-7), 25.75 (d, C-4, C-6), 36.26 (t, C-5), 42.01 (s, C-2, C-8), 87.93 (s, C-1, C-9), 118.98, 126.79, 127.09, 128.15, 128.27 (5 d), 136.21, 146.29 (2 s).

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