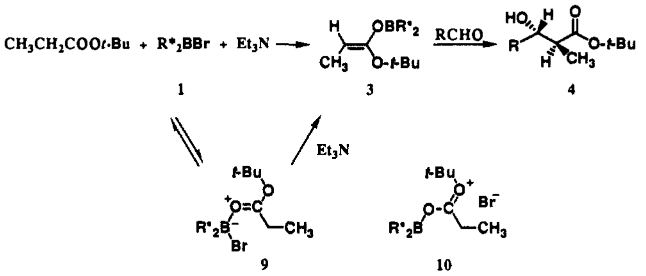
Table I. Reaction of Aldehydes with Propionate Esters Promoted by Bromoborane **1** and Triethylamine To Form Anti Aldols (for Example, **4**)[a]

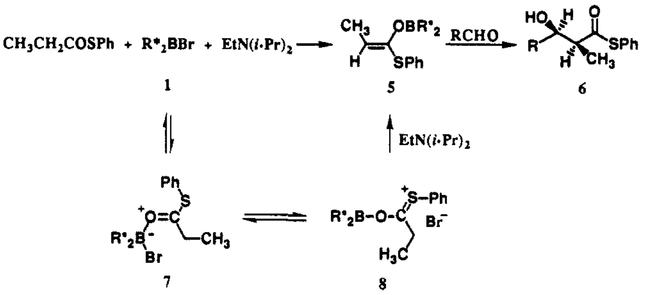
RCHO R	propionate ester	solvent	% yield of aldol	anti:syn	% ee[e]
C_6H_5	*t*-Bu	1:2 toluene–hexane	93	98:2[b]	94
C_6H_5	*t*-Bu	CH_2Cl_2	90	96:4[b]	89
(*E*)-$C_6H_5CH{=}CH$	*t*-Bu	1:2 toluene–hexane	81	99:1[b]	98
(*E*)-$C_6H_5CH{=}CH$	*t*-Bu	CH_2Cl_2	91	96:4[b]	97
cyclohexyl	*t*-Bu	1:2 toluene–hexane	82	94:6[b]	75
cyclohexyl	(+)-menthyl	1:2 toluene–hexane	91	99:1[c]	87
cyclohexyl	(+)-menthyl	CH_2Cl_2	86	98:2[c]	94
$C_6H_5CH_2CH_2$	(+)-menthyl	1:2 toluene–hexane	83	99:1[d]	95
$C_6H_5CH_2CH_2$	(+)-menthyl	CH_2Cl_2	80	97:3[d]	96

[a] Conditions as in text and ref 11. [b] Anti:syn ratios and % ee were determined by HPLC analysis using a chiral Daicel OD column. [c] Analysis by reduction to the corresponding diol mixture with $LiAlH_4$, conversion to the bis MTPA esters, and measurement of 500-MHz ^1H NMR spectra. [d] Anti:syn and de ratios determined by HPLC analysis using a Du Pont Zorbax silica gel column. [e] Absolute configuration, in each case, was determined for the predominating enantiomer (2*S*) by optical rotation and/or comparison with an authentic sample; see: (a) Reference 11. (b) Kim, B. Ph.D. Dissertation, Massachusetts Institute of Technology, Feb 1988.

Scheme I



Scheme II



We believe that the methodology outlined herein will prove to be of considerable utility in synthesis.[11] The reagent **1** and its enantiomer are also highly selective in other enantioselective constructions, e.g., carbonyl allylation.[12]

Supplementary Material Available: Experimental procedures for the preparation of compounds **1**, **2**, **4** (R = C_6H_5), and **6** (R = C_6H_5), as well as key ^1H NMR data for anti aldol products **4** and syn aldol products **6** (5 pages). Ordering information is given on any current masthead page.

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(11) The following procedure for an enantioselective aldol reaction is illustrative. ***tert*-Butyl (2*S*,3*R*)-(+)-2-Methyl-3-hydroxy-3-phenylpropionate (4, R = C_6H_5).** The (*R*,*R*)-(+)-bis[3,5-bis(trifluoromethyl)benzenesulfonamide] **2** (184 mg, 0.24 mmol) dissolved in dry CH_2Cl_2 (3 mL) under argon at 0 °C was treated with BBr_3 (1 M solution in dichloromethane, 480 μL, 0.48 mmol). The stirred solution was heated to 45 °C for 3 h and concentrated under vacuum. Dry dichloromethane (1 mL) was added and evaporated under vacuum. Dry toluene (8 mL) was added, and the resulting mixture was warmed to effect complete solution and then diluted with 16 mL of hexane. The homogeneous solution of bromoborane **1** was cooled to −78 °C, then treated with *tert*-butyl propionate (31 mg, 36 μL, 0.24 mmol), and stirred for 1 min. The resulting solution was treated with triethylamine (27 mg, 37 μL, 0.26 mmol) and stirred for 3.5 h at −78 °C. Benzaldehyde (23 mg, 22 μL, 0.22 mmol) in toluene (0.5 mL) was added over 5 min. The reaction was allowed to proceed for 1.5 h at −78 °C, then quenched by addition of methanol (0.5 mL) at −78 °C followed by dilution with 5 mL of pH 7 buffer. Extractive isolation (ether) afforded the anti aldol **4**, R = C_6H_5, along with the syn diastereoisomer in a ratio of 98:2 as determined by 500-MHz ^1H NMR measurement. Final purification and recovery of (*R*,*R*)-bis(sulfonamide) **2** (92%) were effected by silica gel chromatography (hexane–ethyl acetate, 5:1) to afford **4**, R = C_6H_5 (48.3 mg, 0.20 mmol, 93% yield, 94% ee), as a colorless liquid: $[\alpha]^{20}_D$ +54.66 (*c* 0.73, $CHCl_3$); ^1H NMR (500 MHz, $CDCl_3$) δ 1.02 (d, *J* = 7 Hz, 3 H), 1.44 (s, 9 H), 2.71 (dt, *J* = 15, 7.5 Hz, 1 H), 3.19 (d, *J* = 4.8 Hz, 1 H), 4.70 (dd, *J* = 8.5, 4.5 Hz, 1 H), 7.26–7.35 (m, 5 H); IR (film) 3448 (br), 2976, 2930, 1725, 1368, 1154, 700 cm^{-1}; mass spectrum (FAB, 3-nitrobenzyl alcohol), *m*/*e* (relative intensity), 259 ($M^+ + Na^+$, 100), 203 (18), 198 (7), 173 (48), 119 (7), and 107 (8).

(12) This research was assisted financially by the National Science Foundation and the National Institutes of Health.

Zinc(II) Complexes and Aluminum(III) Porphyrin Complexes Catalyze the Epoxidation of Olefins by Iodosylbenzene

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Iodosylbenzene, OIPh, has been used as a single oxygen atom transfer reagent in a wide variety of studies, usually with the intention of generating reactive intermediates analogous to those occurring naturally in metalloenzyme-catalyzed reactions.[1] In several instances, it has been possible to observe directly high-valent oxo complexes prepared by using iodosylbenzene.[2-4] In the vast majority of cases, however, the intermediacy of high-valent metal oxo intermediates in metal complex catalyzed oxygenations of organic substrates by iodosylbenzene has been assumed or has been asserted on the basis of indirect evidence.[1j-1,3]

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(2) (a) Siddall, T. L.; Miyaura, N.; Huffman, J. C.; Kochi, J. K. *J. Chem. Soc., Chem. Commun.* **1983**, 1185. (b) Samsel, E. G.; Srinivasan, K.; Kochi, J. K. *J. Am. Chem. Soc.* **1985**, *107*, 7606.

(3) Groves, J. T.; Kruper, W. J., Jr. *J. Am. Chem. Soc.* **1979**, *101*, 7613.

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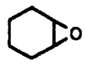
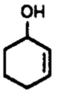
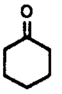
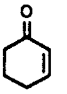
0002-7863/90/1512-4977$02.50/0

Table I. Reaction of Cyclohexene with Iodosylbenzene in the Presence of Complexes of Zinc, Manganese, Copper, and Cobalt[a]

	products, mmol × 10^2						
complex					IPh	epoxide yield[b]	turnover[c]
$Zn_2(1)^{4+}$	11.7	0.30	0.85	0.06	36.2	32	12
$Zn_2(1)^{4+}$ + H_2O[d]	9.0	2.5	2.4	0.7	35.0	26	9.0
$Zn(2)^{2+}$	4.5	0.16	0.62	0.35	30.4	15	2.3
$Zn(3)^{2+}$	0	0	0	0	1.5	0	0
$Zn(CF_3SO_3)_2$	5.6	0.33	1.1	0.8	31.5	18	2.8
$Mn_2(1)^{4+}$	7.2	0.27	*e*	0.4	34.6	21	7.2
$Cu_2(1)^{4+}$	6.2	0.29	*e*	0.9	36.3	17	6.2
$Co_2(1)^{4+}$	5.0	0.25	*e*	0.4	34.2	15	5.0

[a] In a typical experiment, 0.4 mmol of iodosylbenzene was added all at once to a solution of olefin (1.0 mmol) and metal complex (0.01 mmol for the binuclear complexes $M_2(1)^{4+}$ and 0.02 mmol for the others) in 5 mL of anhydrous, deaerated acetonitrile under an inert atmosphere. The reaction mixture was stirred at room temperature for 2 h, during which time 100-μL aliquots of the solution were periodically removed and diluted with 1 mL of acetonitrile. The resulting solution was filtered through a 0.45-μm filter and analyzed by GC/MS. [b] Percent yield of epoxide based on IPh formed. [c] (Millimoles of expoxide)/(millimoles of metal complex). [d] Water (0.036 mL) was added at the beginning of the reaction. [e] Not determined.

Table II. Products Obtained in the Epoxidation of Olefins by OIPh Catalyzed by $Zn_2(1)^{4+}$[a]

olefin	epoxide product	yield, mmol × 10^2	yield,[b] %
cyclohexene	cyclohexene oxide	11.7[c]	32.3
cyclooctene	cyclooctene oxide	8.8	32.3
1-octene	1,2-epoxyoctane	2.0	10
1-hexene	1,2-epoxyhexane	1.9	11
styrene	styrene oxide	0.9	6.6
cis-stilbene	*cis*-stilbene oxide	trace[d]	
	trans-stilbene oxide	1.8	13
	benzaldehyde	0.8	5.6
trans-stilbene	*trans*-stilbene oxide	0.9	9.0
	benzaldehyde	0.23	2.3

[a] See Table I for reaction conditions. [b] Percent yield based on OIPh formed. [c] See Table I for other products. [d] Less than 0.001 mM.

For a number of years, we have studied the reactions of iodosylbenzene with olefins catalyzed by metal ions and complexes of ligands other than porphyrins.[5-8] Our growing suspicion that some of our reactions might be proceeding by direct reaction of the olefin with a metal complex of a hypervalent iodine ligand[9] rather than via high-valent metal oxo intermediates has led us to reexamine the reactivity of non-redox metal complexes as catalysts in our systems. We report here our observation that a binuclear complex of zinc(II) and porphyrin complexes of Al(III) are competent catalysts for olefin epoxidation by iodosylbenzene. We conclude that some of the reactions of the metal-catalyzed iodosylbenzene reactions that have previously been assumed to proceed via high-valent metal oxo intermediates are actually occurring by other mechanisms.

The reactions of iodosylbenzene with olefins in the presence of the triflate ($CF_3SO_3^-$) salts of zinc(II) complexes or $Zn(CF_3SO_3)_2$ itself were studied in acetonitrile. Table I gives the results of a comparative study of the binuclear zinc complex $Zn_2(1)^{4+}$,[10] the mononuclear zinc complexes $Zn(2)^{2+}$ and $Zn(3)^{2+}$, and $Zn(CF_3SO_3)_2$ with cyclohexene as the olefin substrate. (See Chart I for **1**–**3**.) Previously obtained results using $Cu_2(1)^{4+}$ and other binuclear metal complexes of **1** are included for comparison. Table II gives the results of studies of olefin epoxidation by OIPh in the presence of $Zn_2(1)^{4+}$ for a variety of olefins. As can be seen from Table I, the major product in all of these reactions of cyclohexene was cyclohexene oxide; only small amounts of allylic oxidation products were observed. The most striking aspect of the results described in Table I is that the behavior of the zinc(II) complex of **1** so closely resembles the behavior of the analogous copper(II) complex previously reported[7] as well as complexes of **1** with manganese(II) and cobalt(II), suggesting that all of the reactions follow the same mechanism. The direct reaction of iodosylbenzene with the binuclear zinc complex was also studied. An acetonitrile solution of $Zn_2(1)^{4+}$ stirred briefly with excess iodosylbenzene and then filtered rapidly into a solution of cyclohexene gave 0.4 equiv of cyclohexene oxide based on the starting equivalents of $Zn_2(1)^{4+}$. Since iodosylbenzene is insoluble in acetonitrile, we conclude that a soluble complex was formed which contained the elements of iodosylbenzene complexed to $Zn_2(1)^{4+}$ and which reacted with cyclohexene to give epoxide. These results are similar to those obtained previously with the analogous Cu^{II} complex.[7]

We also investigated the effect of adding $H_2{}^{18}O$ to these reactions. The reaction of iodosylbenzene with cyclohexene in the presence of $Zn_2(1)^{4+}$ was carried out under the same conditions described above except that 0.036 mL of $H_2{}^{18}O$ (97% enrichment) was added to the reaction. The presence of water caused the amounts of allylic oxidation products to increase (see Table I), but the major product remained the epoxide, which showed an 86% incorporation of the ^{18}O label. Control experiments established that only a small amount of OIPh exchanged with $H_2{}^{18}O$ in acetonitrile under these conditions in the presence or absence of $Zn_2(1)^{4+}$.[11] We conclude from these experiments that the incorporation of the ^{18}O label into the epoxide comes from attack of $H_2{}^{18}O$ on an intermediate during the course of the epoxidation. It is thus evident that ^{18}O incorporation from $H_2{}^{18}O$ added to OIPh reactions is *not* evidence that metal oxo intermediates are involved,[1-3] since such intermediates cannot be involved in the case of zinc(II).

Having ascertained that non-porphyrin complexes of zinc may catalyze epoxidation reactions by iodosylbenzene, we wondered whether similar reactivity might be found for non-redox-active metalloporphyrin complexes. We therefore investigated the reactivity of $Al^{III}(TPP)X$ (TPP^{2-} = tetraphenylporphinato, X = Cl,

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[6] VanAtta, R. B.; Franklin, C. C.; Valentine, J. S. *Inorg. Chem.* **1984**, *23*, 4121.

[7] Tai, A. F.; Margerum, L. D.; Valentine, J. S. *J. Am. Chem. Soc.* **1986**, *108*, 5006.

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[9] Yang, Y.; Diederich, F. N.; Valentine, J. S., manuscript in preparation.

[10] The complexes $Zn_2(1)^{4+}$,[10] $Zn(2)^{2+}$, and $Zn(3)^{2+}$ were prepared by reaction of zinc triflate with each ligand in acetonitrile followed by precipitation by addition of diethyl ether. They each gave satisfactory elemental analyses.

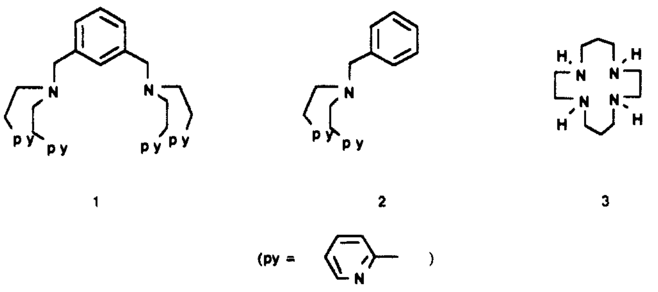
[11] A mixture of iodosylbenzene (100 mg, 0.45 mmol) and $H_2{}^{18}O$ (125 μL, 6.9 mmol, 97% enrichment) in 3 mL of acetonitrile was stirred for 30 min. The solid iodosylbenzene was filtered and dried in vacuo in the presence of $CaSO_4$ for 1 day. The infrared spectrum of this solid showed only bands attributable to $^{16}OIPh$ and not to $^{18}OIPh$. Moreover, this solid was used to epoxidize cyclohexene, and the resulting cyclohexene oxide was shown to contain less than 6% ^{18}O. A similar experiment with $Zn_2(1)^{4+}$ added also showed little incorporation of ^{18}O into OIPh. Cyclohexene oxide was also found not to exchange with $H_2{}^{18}O$ in acetonitrile in the presence of $Zn_2(1)^{4+}$.

Table III. Products Obtained in the Epoxidation of Olefins by OIPh Catalyzed by Al(TPP)X (X = Cl, OH)[a]

catalyst	olefin (concn, mmol)	product(s) detected	yield, mmol	yield,[b] %	turnover[c]
Al(TPP)Cl	*cis*-stilbene (5)	IPh	0.29		
		cis-stilbene oxide	0.18	62	9.3
		trans-stilbene oxide	0.005		
		benzaldehyde	0.0008		
Al(TPP)Cl	*cis*-stilbene (1)	IPh	0.18		
		cis-stilbene oxide	0.037	22	2.0
		trans-stilbene oxide	0.003		
		benzaldehyde	0.001		
Al(TPP)Cl	*trans*-stilbene (1)	IPh	0.14		
		cis-stilbene oxide	0.003		
		trans-stilbene oxide	0.006	6.4	0.5
		benzaldehyde	0.002		
Al(TPP)Cl	cyclohexene (5)	IPh	0.20		
		cyclohexene oxide	0.016	8	0.8
Al(TPP)OH[d]	cyclohexene (5)	IPh	0.22		
		cyclohexene oxide	0.054	25	5

[a] For the experiments using Al(TPP)Cl, 0.4 mmol of iodosylbenzene was added all at once to a solution of olefin and Al(TPP)Cl (0.02 mmol) in 2 mL of toluene under an inert atmosphere. The reaction mixture was stirred at room temperature for 1 day, after which time 100 μL of the solution was removed and diluted with 1 mL of acetonitrile. The resulting solution was filtered through a 0.45-μm filter and analyzed by HPLC and GC/MS. [b] Percent yield of epoxide based on IPh formed. [c] (Millimoles of epoxide)/(millimoles of metal complex). [d] In this experiment, 0.22 mmol of iodosylbenzene was added to a solution of olefin, Al(TPP)OH (0.011 mmol), and $Li(CF_3SO_3)$ (0.044 mmol) in 2 mL of acetonitrile. Other conditions were the same as in the previous experiments.

Chart I



OH) as catalysts for such reactions. As can be seen from the results in Table III, Al(TPP)X is also a competent catalyst for epoxidation reactions of iodosylbenzene.[12,13] Moreover, the reactivity pattern observed for *cis*- and *trans*-stilbenes is similar to that observed in the case of Fe^{III}(TPP)Cl-catalyzed reactions, i.e., *cis*-stilbene is significantly more reactive than *trans*-stilbene and the product in the case of the former is predominantly *cis*-stilbene oxide,[14] although the Al(TPP)X-catalyzed reactions are significantly slower than those catalyzed by Fe(TPP)Cl.[14]

On the basis of the studies described above, we conclude that metal complexes can catalyze olefin epoxidation by pathways that do not involve high-valent metal oxo intermediates and that ^{18}O incorporation from $H_2{}^{18}O$ cannot be used as evidence to support such intermediates. In other work, we have obtained results suggesting that the alternative reaction pathway may involve metal complexes containing the elements of OIPh and that the first step of the reaction mechanism may best be described as electrophilic attack of I^{III} on the olefin.[9,15] On the basis of our results, we believe that the assumption that metal complex catalyzed reactions of iodosylbenzene invariably involve high-valent metal oxo intermediates should be reconsidered for porphyrin and nonporphyrin systems alike.

Acknowledgment. Financial support from the National Science Foundation is gratefully acknowledged.

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(12) We submitted our Al(TPP)Cl catalyst for analysis by atomic absorption and ascertained that it contained 62 ppm Fe, >1 ppm Mn, and 7.6 ppm Cr, insufficient amounts to attribute the observed catalytic activity to transition-metal contaminants.

(13) Lithium triflate was required in order for Al(TPP)OH to be reactive, suggesting that the triflate anion plays a role either in solubilizing OIPh or in generating the active oxidant. Similar anion effects were observed previously.[8]

(14) Groves, J. T.; Nemo, T. E.; Myers, R. S. *J. Am. Chem. Soc.* **1979**, *101*, 1032.

(15) A related proposal has been made for a different system in the following: Moriarty, R. M.; Penmasta, R.; Prakash, I. *Tetrahedron Lett.* **1985**, *26*, 4699.

Quantitative Detection of Remotely Disposed Chiral Centers Using Selenium-77 Nuclear Magnetic Resonance Spectroscopy

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The application of ^{77}Se NMR spectroscopy, via selone **1**,[1] to the detection of enantiomeric excesses at remote chiral centers is described.[2] There exists a plethora of methods for both determination of enantiomeric excesses and, to a lesser extent, absolute configurational assignment.[3] Current NMR spectroscopic methods take advantage of either the formation of contact solution

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† Permanent address: University of California, Los Alamos National Laboratory.

(1) A U.S. Patent application has been filed to cover the use of **1** for the detection of enantiomeric excesses and absolute configurational assignment at chiral centers.

(2) For an application of ^{77}Se NMR for the determination of enantiomeric purity of alcohols, see: Michelsen, P.; Annby, U.; Gronowitz, S. *Chem. Scr.* **1984**, *24*, 251.

(3) *Asymmetric Synthesis*; Morrison, J. D., Ed.; Academic: New York, 1983-1985. Sullivan, G. R. *Topics in Sterochemistry*; Eliel, E. L.; Allinger, N. L.; Wilen, S. H., Eds.; Wiley-Interscience: New York, 1978; p 263. *Methods in Stereochemical Analysis*; Marchand, A. P., Ed.; VCH Publishers, Inc.: New York, 1986; Vols. 1-9. For chromatographic separations, see: Francotte, E.; Lohmann, D. *Helv. Chim. Acta* **1987**, *70*, 1569. Maibaun, J. *J. Chromatogr.* **1988**, *436*, 269. *Chromatographic Chiral Separations. Chromatographic Science Series 40*; Zief, M., Crane, L. J., Eds.; Marcel Dekker: New York and Basel, 1988. For chiral NMR shift reagents, see: Pirkle, W. H.; Hoover, D. J. In *Topics in Sterochemistry*; Eliel, E. L., Allinger, N. L., Wilen, S. H., Eds.; Wiley-Interscience: New York, 1982; p 287. *Methods in Stereochemical Analysis*; Morrill, T. C., Ed.; VCH Publishers, Inc.: New York, 1986; Vol. 5. For direct chirality determination of secondary alcohols, see: Kato, K. *J. Am. Chem. Soc.* **1990**, *112*, 254.

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