of 1 now showed that a new vinyl species had formed which may be $Cp^*_2Hf(OH)CH{=}CH_2$: δ (C_6D_6) 1.80 (s) (Cp^*), 4.18 (s) (OH) 6.83 (dd, J_{HH} = 20 and 15 Hz) (CH_2=), 6.54 (dd, J_{HH} = 16 and 5 Hz) (CH_2=), 5.39 (dd, J_{HH} = 20 and 5 Hz) (–CH=) ppm, as well as weak peaks at δ 1.85 (s) (Cp^*) and 2.97 (s) (OH) ppm corresponding to $Cp^*_2Hf(OH)_2$.

Cp^*_2HfH(crotyl) (8). A sample of 0.485 g (1.08 mmol) of $Cp^*_2HfH_2$ was weighed into a 25-mL flask of a swivel-frit assembley, and 10 mL of toluene was condensed into the flask. The flask was cooled to –196 °C, and butadiene (1.09 mmol) was condensed in from a gas bulb. The reaction mixture was warmed to –78 °C, stirred for 10 min, and then allowed to warm to room temperature. The almost colorless solution was then stirred for 23 h at room temperature, during which time the solution turned yellow. The solvent was removed under reduced pressure, and 10 mL of petroleum ether was condensed in. The solution was filtered, concentrated, and then cooled to –78 °C when a pale yellow microcrystalline compound formed. This was filtered and dried to give 0.13 g (24%) of 8: mp 136–145 °C, IR ν(Hf–H) 1578 (w), 1624 (sh) cm^{-1}. Anal. Calcd for $C_{24}H_{38}Hf$: C, 57.08; H, 7.58. Found: C, 57.51; H, 7.66.

$Cp^*_2HfCH_2CH_2CH_2CH(CH_3)$ (9). A 50-mL flask was loaded with 0.52 g (1.15 mmol) of $Cp^*_2HfH_2$, and 10 mL of toluene was condensed in at –78 °C. The solution was then cooled to –196 °C, and 1,4-pentadiene (1.15 mmol) was condensed in from a gas bulb. The reaction solution was allowed to warm to room temperature and was stirred at this temperature for 23 h. The solvent was removed to yield a yellow residue, and 15 mL of petroleum ether was condensed in. The clear yellow solution was concentrated and cooled to –78 °C. The resulting solid was filtered off to give 0.34 g (57%) of lemon yellow crystals of 9: mp 166–171 °C. Anal. Calcd for $C_{20}H_{32}Hf$: C, 57.85; H, 7.77; M, 519. Found: C, 57.66; H, 7.51; M, 467. The mass spectrum showed peak envelopes with the most abundant peak of the envelope at 518 (M^+): 485, 478 ($M - C_3H_6$)$^+$, 466, 450 ($M - C_5H_{10}$)$^+$, and 223 ($M - C_5H_{10}$)$^{2+}$ (assignments in parentheses).

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Registry No. 1, 138060-38-5; 2, 138054-15-6; 3, 138054-16-7; 4, 138054-17-8; 5, 138054-18-9; 6, 138054-19-0; 7, 138054-20-3; 8, 138128-19-5; 9, 138054-21-4; 10, 138054-22-5; 11, 138054-23-6; $Cp^*_2HfH_2$, 81956-87-8; Cp^*_2(H)Hf(ethylallyl), 138054-24-7; $Cp^*_2HfH(CH_2)_4CH{=}CH_2$, 138054-25-8; Cp^*_2(H)Hf$(CH_2)_4CH_3$, 138054-26-9; $Cp^*_2ZrCH_2CH_2CH_2CH(CH)_3$, 138054-27-0; $Cp^*_2ZrCH_2CH_2CH_2CH_2CH(CH_3)$, 138054-28-1; $[Cp^*_2HfI]_2(\mu$-$(CH_2)_5)$, 138054-29-2; $Cp^*_2ZrH_2$, 61396-34-7; $Cp^*_2TiH_2$, 12701-41-6; $Cp^*_2(H)ZrCH_2CH_2CH_2CH_2CH_2CH_2Zr(H)Cp^*_2$, 138060-39-6; 1,4-pentadiene, 591-93-5; 1,5-hexadiene, 592-42-7; butadiene, 106-99-0; acetylene, 74-86-2; 1,6-heptadiene, 3070-53-9; allene, 463-49-0.

Shape-Selective and Asymmetric Cyclopropanation of Alkenes Catalyzed by Rhodium Porphyrins

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Rhodium porphyrins catalyze the cyclopropanation of simple alkenes by diazo esters. Functionalized catalysts that mediate selective cyclopropanation reactions might be of use in organic synthesis, particularly since the porphyrin catalysts generally provide syn cyclopropyl esters as the major product. In this report we examine the possibility of engineering shape selectivity and asymmetric induction into this system. We show that the iodorhodium derivative of an optically active macrocycle, the "chiral wall" porphyrin, does mediate the enantioselective cyclopropanation of prochiral olefins. Enantiomeric excesses of 10–60% are observed. In addition, the substrate selectivities of hindered (RhTMPI) and unhindered (RhTTPI) simple porphyrins were assessed. In both cases, mono-, di-, and trisubstituted aliphatic olefins undergo reaction at nearly equivalent rates but tetrasubstituted alkenes are cyclopropanated poorly, especially when the crowded catalyst is employed. In the case of bulkier aromatic alkenes, extremely high cis/trans substrate selectivity is observed. These observations have led to a model for the geometry of interaction between the putative metallocarbene and the alkene that rationalizes the relative reactivity of the many substrates investigated. The relevance of these results to the rational design of more selective asymmetric catalysts is also discussed.

Metalloporphyrins mediate a number of interesting stoichiometric and catalytic reactions, including olefin epoxidation[1-5] and cyclopropanation[6], alkane hydroxylation,[7,8] Diels–Alder cycloadditions,[9] cleavage of amides,[10] and a number of other processes. Recently, several laboratories have made progress toward engineering novel selectivities into these reactions for the purposes of mimicking the properties of certain heme-containing enzymes or creating novel reagents for organic synthesis.

Much of this activity has focused on alkene epoxidation and alkane hydroxylation systems which mimic the cytochrome P-450 family of monooxygenases, and a number of reports of interesting asymmetric and shape-selective

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(1) Groves, J. T.; Nemo, T. E.; Myers, R. S. *J. Am. Chem. Soc.* **1979**, *101*, 1032–1033.
(2) Groves, J. T.; Kruper, W. J., Jr.; Haushalter, R. C. *J. Am. Chem. Soc.* **1980**, *102*, 6375–6377.
(3) Traylor, T. G.; Marsters, J. C.; Nakano, T.; Dunlap, B. E. *J. Am. Chem. Soc.* **1985**, *107*, 5537–5539.
(4) Collman, J. P.; Kodadek, T.; Raybuck, S. A.; Meunier, B. *Proc. Natl. Acad. Sci. U.S.A.* **1983**, *80*, 7039–7041.
(5) Groves, J. T.; Quinn, R. *J. Am. Chem. Soc.* **1985**, *107*, 5790–5792.
(6) Callot, H. J.; Metz, F.; Piechoki, C. *Tetrahedron* **1982**, 2365–2369.
(7) Smegal, J. A.; Hill, C. L. *J. Am. Chem. Soc.* **1983**, *105*, 3515–3521.
(8) Collman, J. P.; Tanaka, H.; Hembre, R. T.; Brauman, J. I. *J. Am. Chem. Soc.* **1990**, *112*, 3689–3690.

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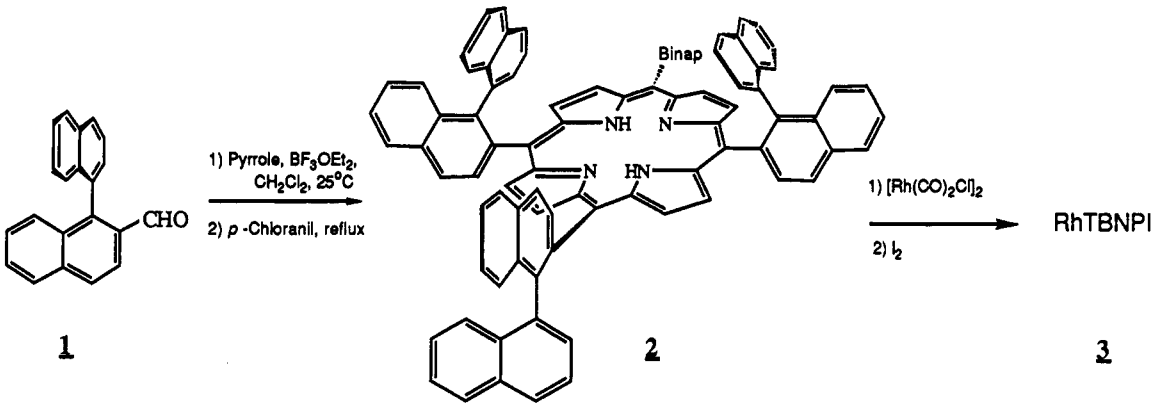


Figure 1. Synthesis of the "chiral wall" porphyrin and its iodorhodium(III) derivative.

catalysts have been published.[11-19] Much less work has been done on the other reactions mentioned above, though some of them appear to hold promise as synthetic methods. For example, Callot has reported that iodorhodium porphyrins catalyze the cyclopropanation of alkenes by ethyl diazoacetate (EDA) in good yields and with retention of alkene stereochemistry.[6] An interesting facet of this reaction is that the syn cyclopropyl ester is usually the predominant product, the syn/anti ratio increasing with the bulk of the porphyrin. While there is already an abundance of synthetically useful cyclopropanation catalysts,[20] including some excellent asymmetric systems,[21-25] all of them provide mixtures of syn and anti products with the anti predominating. The relative ease with which the steric and chemical characteristics of the metalloporphyrin "active site" can be manipulated provides the opportunity to develop new shape-selective and asymmetric cyclopropanation systems which might be of utility in organic synthesis. Our initial efforts toward these goals are summarized in this report. Some of this work has been communicated.[19,26]

Results

Synthesis and Characterization of the Iodorhodium "Chiral Wall" Porphyrin.

We have communicated the synthesis of $5\alpha,10\beta,15\alpha,20\beta$-tetrakis[(*R*)-1,1′-binaphth-2-yl]porphyrin ($TBNPH_2$), which we call the "chiral wall" porphyrin (**2** in Figure 1), as well as its chloromanganese derivative.[19] Full details are provided in the Experimental Section. Briefly, optically pure (*R*)-1,1′-binaphth-2-aldehyde (**1**) was obtained according to the procedure of Meyers et al.[27] Condensation of the aldehyde with pyrrole to form a tetrapyrrole was effected using a modified Lindsey procedure,[28] with dichloromethane as solvent and BF_3–etherate and EtOH as cocatalysts. In situ oxidation with *o*-chloranil provided the fully aromatic macrocycle. The yield of the cyclization reaction is usually 8–11%, although yields of up to 16% have been realized. These reactions were generally allowed to proceed for 3–4 days, an incubation period much longer than that routinely used for Lindsey condensations with many other aromatic aldehydes. Extensive optimization studies have shown that shorter times result in inferior yields.

The 500-MHz ^1H NMR spectrum of the crude porphyrin product clearly reveals the presence of multiple atropisomers (data not shown). The desired $\alpha,\beta,\alpha,\beta$ isomer could be purified by flash chromatography on Florisil. None of the other atropisomers could be resolved. All of the 13 unique aromatic protons in the desired porphyrin could be assigned from the 2-D COSY ^1H NMR (Figure 2), confirming the $\alpha,\beta,\alpha,\beta$ atropisomeric assignment. The iodorhodium derivative **3** (Figure 1) was produced by the literature procedure[29] (treatment with $Rh_2Cl_2(CO)_4$, followed by oxidation with I_2).

Asymmetric Cyclopropanation Using the Iodorhodium Chiral Wall Porphyrin Catalyst. The rhodium chiral wall porphyrin **3** is an extremely active catalyst for alkene cyclopropanation in the presence of ethyl diazoacetate; thousands of turnovers of the catalyst were observed routinely. The syn cyclopropyl ester was the major product in nearly all of the reactions. The observed enantioselectivities for the substrates tested so far are moderate to poor (Table I).

In an attempt to improve the enantio- and diastereoselectivities of the reaction, we examined the effect of temperature (Table I). At 0 °C, a substantial improvement in the syn/anti ratio in the cyclopropanation of allylbenzene was observed but the enantioselectivities improved only slightly. Unfortunately, the rate of the porphyrin-catalyzed cyclopropanation reaction is quite tempera-

(9) Bartley, D. W.; Kodadek, T. *Tetrahedron Lett.* **1990**, *31*, 6303–6305.
(10) Aoyama, T.; Motomura, T.; Ogoshi, H. *Angew. Chem., Int. Ed. Engl.* **1989**, *28*, 921–922.
(11) Groves, J. T.; Nemo, T. E. *J. Am. Chem. Soc.* **1983**, *105*, 5786–5791.
(12) Cook, B. R.; Reinert, T. J.; Suslick, K. S. *J. Am. Chem. Soc.* **1986**, *108*, 7281–7286.
(13) Collman, J. P.; Brauman, J. I.; Hiyashi, T.; Kodadek, T.; Raybuck, S. A. *J. Am. Chem. Soc.* **1985**, *107*, 2000–2005.
(14) Collman, J. P.; Zhang, X.; Hembre, R. T.; Brauman, J. I. *J. Am. Chem. Soc.* **1990**, *112*, 5356–5357.
(15) Groves, J. T., Newmann, R. *J. Am. Chem. Soc.* **1987**, *109*, 5045–5047.
(16) Groves, J. T.; Myers, R. S. *J. Am. Chem. Soc.* **1983**, *105*, 5791–5796.
(17) Groves, J. T.; Viski, P. *J. Org. Chem.* **1990**, *55*, 3628–3634.
(18) Mansuy, D.; Battioni, P.; Renaud, J.-P.; Guerin, P. *J. Chem. Soc., Chem. Commun.* **1985**, 155–156.
(19) O'Malley, S.; Kodadek, T. *J. Am. Chem. Soc.* **1989**, *111*, 9116–9117.
(20) Doyle, M. P. *Chem. Rev.* **1986**, *86*, 919–939.
(21) Aratani, T. *Pure Appl. Chem.* **1985**, *57*, 1839–1844.
(22) Fritschi, H.; Leutenegger, U.; Pfaltz, A. *Angew., Chem. Int. Ed. Engl.* **1986**, *25*, 1005–1006. Pfaltz, A. *Modern Synthetic Methods*; Scheffold, R., Ed.; Springer: Berlin, 1989; Vol. 5, pp 199–248. Fritschi, H.; Leutenegger, U.; Pfaltz, A. *Helv. Chim. Acta* **1988**, *71*, 1553–1565.
(23) Lowenthal, R. E.; Abiko, A.; Masamune, S. *Tetrahedron Lett.* **1990**, *31*, 6005–6008.
(24) Evans, D. A.; Woerpel, K. A.; Hinman, M. M.; Faul, M. M. *J. Am. Chem. Soc.* **1991**, *113*, 726–728.
(25) Doyle, M. P.; Brandes, B. D.; Kazala, A. P.; Pieters, R. J.; Jarstfer, M. B.; Watkins, L. M.; Eagle, C. T. *Tetrahedron Lett.* **1990**, *31*, 6613–6616.
(26) O'Malley, S.; Kodadek, T. *Tetrahedron Lett.* **1991**, *32*, 2445–2448.
(27) Meyers, A. I.; Lutomski, K. A. *J. Am. Chem. Soc.* **1982**, *104*, 879–881.
(28) Lindsey, J. S.; Schreiman, I. C.; Hsu, H. C.; Kearney, P. C.; Marguerettaz, A. M. *J. Org. Chem.* **1987**, *52*, 827–839.
(29) Callot, H. J.; Schaeffer, E. *Nouv. J. Chim.* **1980**, *4*, 311–314.

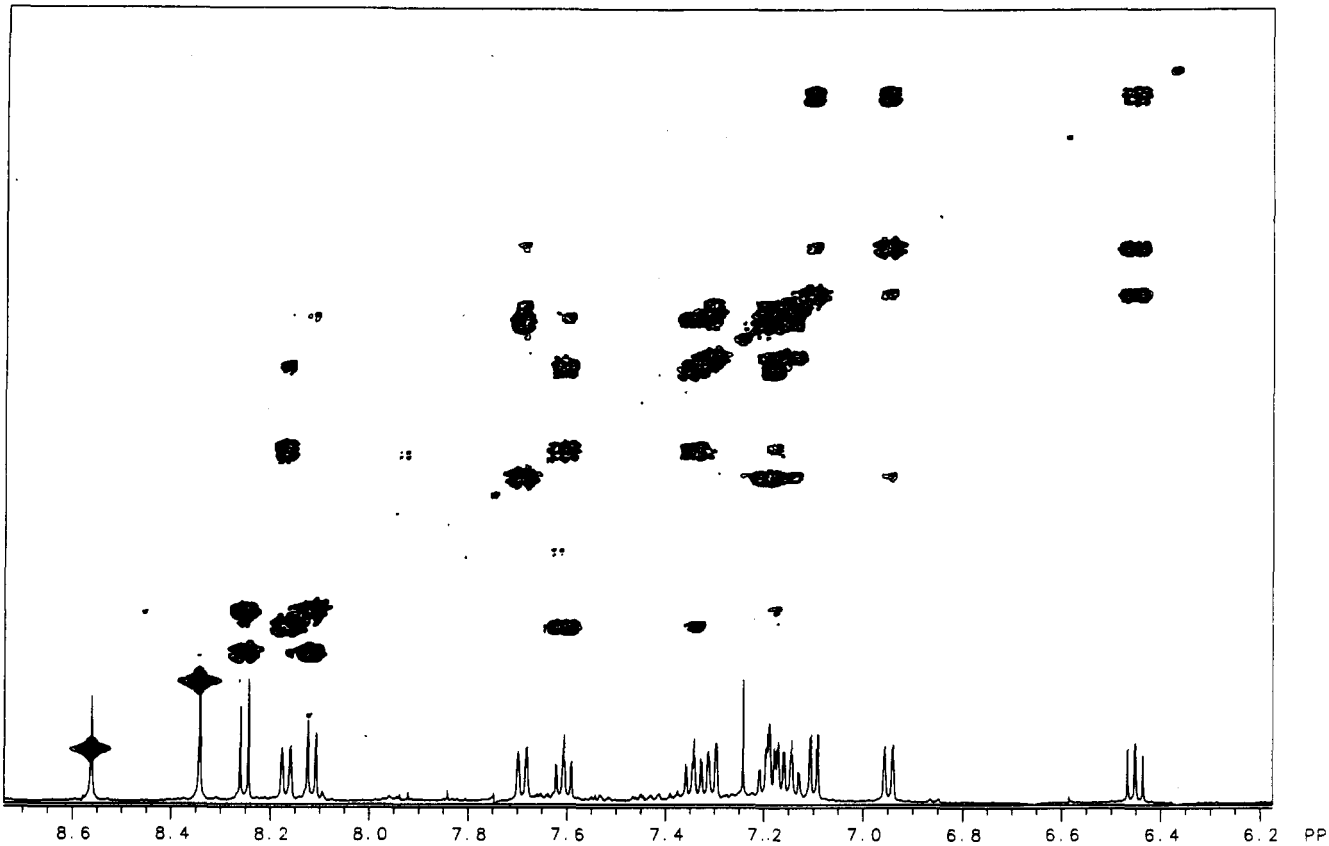
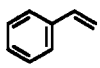
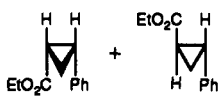
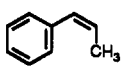
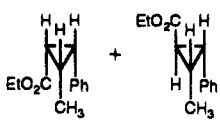
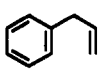
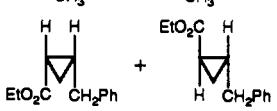
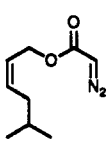
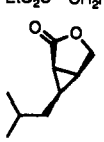


Figure 2. 500-MHz 2-D COSY ^{1}H NMR spectrum of $TBNPH_2$ (**2**). The observation of 13 unique binaphthyl protons and two singlets corresponding to the β-pyrrolic protons confirms the α,β,α,β atropisomeric assignment.

Table I. Asymmetric Cyclopropanation of Alkenes with RhTBNPI and Ethyl Diazoacetate[a]

substrate	products	T (°C)	% ee syn	% ee anti	syn/anti ratio	turnovers
	 (+)-(1*S*,2*R*)	0	10	nd	2.3	2000
		0	20	50	7.8	4500
		22	15	30	4.0	5800
		0	45	60	4.3	550
		22	40	40	1.0	1850
			10			

[a] For the styrene syn product, measurement of the optical rotation allowed identification of the absolute configuration of the predominant enantiomer as (+)-(1*S*,2*R*);[21] other absolute configurations have not been assigned.

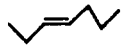
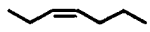
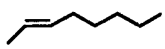
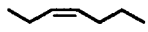
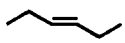
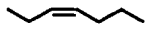
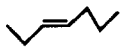
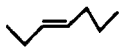
ture-sensitive, and it is not practical to conduct reactions below 0 °C.

It occurred to us that increasing the steric congestion at the active site by using a bulky diazo ester might improve either the diastereoselectivity or the enantiomeric excess, but these efforts proved unsuccessful. Neither 2,6-di-*tert*-butyl-4-methylphenyl diazoacetate[30] nor *tert*-butyl diazoacetate gave detectable cyclopropanation of *cis*-β-methylstyrene under the standard reaction conditions in the presence of catalyst **3**.

Shape-Selective Cyclopropanation Using Simple Porphyrins. In their pioneering study, Callot and coworkers mentioned that trans-disubstituted olefins are poorer substrates than the cis isomers in rhodium porphyrin catalyzed cyclopropanation reactions,[6] suggesting that this process might exhibit a shape selectivity similar to that of porphyrin-catalyzed epoxidation reactions. A shape-selective catalyst might be of synthetic utility for the selective cyclopropanation of polyenes, and in addition,

(30) Doyle, M. P.; Bagheri, V.; Wandless, T. J.; Harn, N. K.; Brinker, D. A.; Eagle, C. T.; Loh, K.-L. *J. Am. Chem. Soc.* **1990**, *112*, 1906–1912.

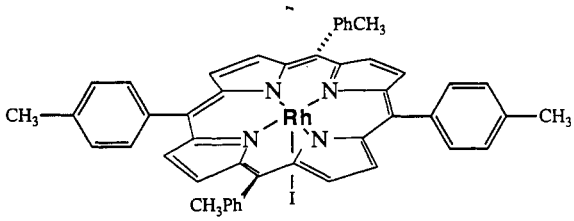
Table II. Competitive Cyclopropane Formation from Representative Olefin Pairs and Ethyl Diazoacetate with RhTTPI and RhTMPI Catalysts

olefin		RhTTPI		RhTMPI	
A	B	ratio A′/B′[a]	yield[b] (%)	ratio A′/B′[a]	yield[b] (%)
		1.6	62	3.0	60
		1.2	74	3.6	72
		1.0	61	2.8	70
		5.3	52	49	56
		1.9	23	4.0	25
		0.9	50	3.3	29
		0.5	66	1.0	74
		3.3	59	16	24
		0.8	67	0.70	31
		2.7	57	9.5	26

[a] A′ and B′ represent the corresponding cyclopropane ester products of olefins A and B. These values represent the mixture of the syn and anti isomers. [b] Based on ethyl diazoacetate.

an examination of a broad range of substrates might provide us with at least a crude picture of how the alkene is oriented with respect to the porphyrin in the product-determining step. Such information could be of considerable utility in the design of new asymmetric catalysts.

Table II shows the results of a number of competitive cyclopropanation reactions between simple mono-, di-, tri-, and tetrasubstituted aliphatic alkenes using ethyl diazoacetate as the carbene source and either iodorhodium tetra-*p*-tolylporphyrin (RhTTPI, **4**) or the much bulkier iodorhodium tetramesitylporphyrin (RhTMPI, **5**) as the catalyst. In each case, the two substrates were present at equivalent initial concentrations. Since the olefins were present in excess over the ethyl diazoacetate, the alkene pools were not depleted significantly in the course of the reaction and the observed product ratios therefore closely resemble the true selectivities.



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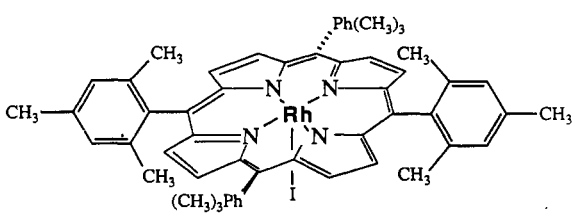
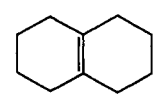


5

It is clear that the porphyrin does not display simple electrophilic selectivity. Most strikingly, 1-hexene, the least electron-rich substrate, is cyclopropanated preferentially (5.3/1) in the presence of an equal amount of 2,3-dimethyl-2-butene using RhTTPI as the catalyst and almost exclusively (49/1) with the bulkier RhTMPI catalyst. Under identical conditions, we found that a copper sulfate catalyzed reaction yielded a 0.8 ratio of products derived from the mono- and tetrasubstituted alkenes. Clearly, the porphyrin catalyst behaves differently than more traditional systems. The increased selectivity of the TMP ligand for less highly substituted alkenes over TTP is a general trend. For example, *cis*-3-heptene is more reactive than 2,3-dimethyl-2-butene by a factor of 3.3 in the presence of RhTTPI, while a 16/1 ratio of the cyclopropanes derived from these olefins is observed with RhTMPI as the catalyst.

The poor reactivity exhibited by 2,3-dimethyl-2-butene is shared by another tetrasubstituted alkene, **6**, and suggests that tetrasubstituted alkenes are generally poor substrates for the porphyrin catalysts. For **6**, no reaction at all was observed using porphyrin **5** as catalyst and only minor amounts of cyclopropane products were observed with the less hindered catalyst **4** (data not shown).

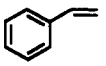
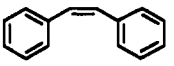
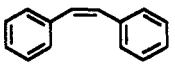
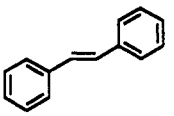
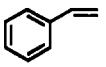
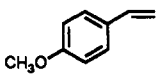
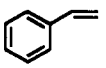
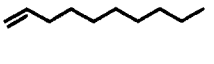


6

In contrast to Callot's earlier report,[6] most trans-disubstituted alkenes are almost as reactive as their cis counterparts in our hands. For example, in RhTTPI-catalyzed competitive reactions with 2-methyl-2-pentene, *cis*- and *trans*-3-heptene are about equally reactive. A run containing *cis*-3-heptene and *trans*-2-octene exhibited only a 2-fold preference for the cis alkene. With the bulkier TMP ligand, the preference for the cis isomer increased, but not dramatically.

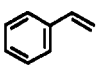
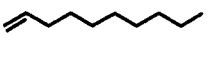
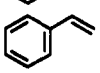
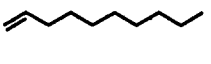
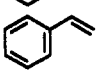
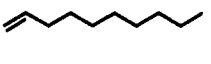
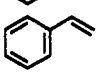
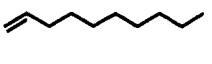
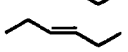
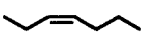
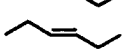
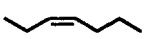
However, much more pronounced selectivities were observed when the alkene substituents were bulky and stiff, such as aromatic rings (Table III). For example, *cis*-stilbene is cyclopropanated exclusively in the presence of the trans isomer by RhTTPI. Neither alkene is a substrate for the bulkier RhTMPI catalyst. Interestingly, with both the RhTMPI and RhTTPI catalysts, a competitive reaction containing styrene and *cis*-stilbene yielded only the styrene-derived cyclopropanes. This result should be

Table III. Competitive Cyclopropane Formation from Representative Aryl-Substituted Olefin Pairs and Ethyl Diazoacetate with RhTTPI and RhTMPI Catalysts

olefin		RhTTPI		RhTMPI	
A	B	ratio A′/B′[a]	yield[b] (%)	ratio A′/B′[a]	yield[b] (%)
		>100[c]	61	>100[c]	75
		>100[c]	31	NR[d]	
		1.0	82		
		3.5	91	2.5	89

[a] A′ and B′ represent the corresponding cyclopropane ester products of olefins A and B. These values represent the mixture of the syn and anti isomers. [b] Based on ethyl diazoacetate. [c] No minor product detected. [d] Cyclopropane ester products were not detected.

Table IV. Competitive Cyclopropane Formation from Representative Olefin Pairs and Ethyl Diazoacetate with RhTTPI Catalyst: Effects of Temperature

olefin				
A	B	temp (°C)	ratio A′/B′[a]	yield[b] (%)
		−25	3.4	96
		0	3.6	87
		22	3.5	91
		60	3.2	98
		0	0.9	51
		22	0.9	56
		60	0.9	50

[a] A′ and B′ represent the corresponding cyclopropane ester products of olefins A and B. These values represent the mixture of the syn and anti isomers. [b] Based on ethyl diazoacetate.

compared to the nearly equivalent reactivities of aliphatic, straight-chain monosubstituted and cis-disubstituted alkenes (Table II).

Since the mechanism of carbene transfer from the metal to the alkene is unknown and could involve transient radical or cationic intermediates, we wanted to ensure that electronic factors were not somehow the cause of the much greater selectivity observed with aromatic substrates. Therefore, we performed a reaction containing equivalent amounts of styrene and 1-decene. The aromatic alkene was found to be only slightly more reactive (Table III). In addition, *p*-methoxystyrene and styrene are equally reactive in the RhTTPI-catalyzed reaction. Therefore, it seems unlikely that a radical or cationic intermediate is involved in the product-determining step and that the results of competitions utilizing both aliphatic and aromatic olefins are dominated by steric factors.

In order to probe the effect of temperature on the shape selectivity, we carried out several competitive runs with styrene and 1-decene as substrates and RhTTPI as the catalyst (Table IV). The product ratio was not temperature-sensitive, remaining about 3.5/1 in favor of the aromatic alkene from +60 to −25 °C. A similar result was obtained for competitive reactions containing *trans*-3-hexene and *cis*-3-heptene; the ratio of products resulting from cyclopropanation of the trans and cis alkenes was 0.89 at both 0 and 60 °C. In both cases, the overall rate of reaction was much slower at lower temperatures. The insensitivity of the product ratio to the temperature is somewhat surprising. In the absence of detailed kinetic studies, particularly the order of the reaction in porphyrin, olefin, and EDA, it is difficult to provide an explanation for this observation.

Discussion

We have begun to examine the possibility of developing porphyrin-based catalytic systems for selective alkene cyclopropanation. In this report two major issues are addressed: enantioselectivity and shape selectivity.

The porphyrin-catalyzed reaction is novel in that it produces the syn cyclopropyl esters selectively in some cases, particularly when bulky porphyrins are employed. Therefore, an enantioselective version of this process would be a useful complement to the several asymmetric catalysts that provide predominantly anti cyclopropyl esters.[21-25] As a first step toward developing such a system, we evaluated the rhodium "chiral wall" porphyrin **3** as an asymmetric cyclopropanation catalyst. While the chemical efficiency of the system is excellent, with several thousand turnovers observed routinely, the enantioselectivities are considerably below what would be synthetically useful (Table I). This was true for both intermolecular reactions and the single intramolecular case examined. Lowering the temperature from 25 to 0 °C increases the diastereoselectivity of the process but has only a small effect on the enantioselectivity. Clearly, significant modifications to the porphyrin

superstructure must be made if synthetically useful enantiomeric excesses are to be achieved. Nonetheless, these experiments are significant in that they represent the first examples of porphyrin-catalyzed asymmetric cyclopropanation reactions. In addition, the syn cyclopropyl ester was the major product in each case, making this the first syn-selective asymmetric catalyst.

To explore the issue of shape selectivity, we carried out a number of competitive cyclopropanation reactions. While both steric and electronic factors contribute to the overall reactivity of any particular alkene, it seems that steric factors are of primary importance. This view is based on various indications that the catalyst is not terribly sensitive to the electron density of the alkene substrate. For example, the ratio of products in competitions between different para-substituted styrenes is insensitive to the nature of the para substituent (Table III). Furthermore, styrene, an aromatic olefin, and 1-decene, an aliphatic olefin, have similar reactivities. Finally, the ratio of products obtained from competitions between aliphatic olefins does not correlate with the electron density of the substrates. Therefore, we will discuss the results of the competition reactions in terms of steric selectivities although this is clearly an approximation.

Taken together, the results shown in Tables II and III support the following conclusions. First, neither RhTTPI (**4**) nor the bulkier RhTMPI (**5**) are particularly discriminating catalysts in competitions between primary, secondary, and tertiary aliphatic alkenes. While cis-disubstituted aliphatic alkenes are somewhat more reactive than the trans isomers in the presence of the RhTTPI catalyst, the differences are quite small. RhTMPI is somewhat more selective, but again, the selectivities are not large. However, more impressive ratios are seen in competitions involving the tetrasubstituted alkene 2,3-dimethyl-2-butene, which is a poor substrate for the RhTTPI catalyst and a terrible one for RhTMPI (Table II).

The porphyrin catalysts are much more discriminating when bulky aromatic olefins are used as substrates (Table III). The RhTTPI-catalyzed cyclopropanation of *cis*- and *trans*-stilbene yielded products from the cis alkene only. The RhTMPI catalyst was incapable of processing either substrate. Moreover, with these bulkier substrates, we observed a very high selectivity for a terminal alkene (styrene) over a cis-disubstituted alkene (*cis*-stilbene) with both catalysts.

To explain these observations, we propose the model shown in Figure 3 (upper structure). It depicts a geometry for the alkene–metallocarbene interaction that is reminiscent in some respects to the perpendicular approach of olefins to the active high-valent oxo complex in the P-450 model systems that has been invoked to explain the shape selectivity observed in those systems.[11] Indeed, Callot and co-workers have proposed a perpendicular approach for the cyclopropanation reaction[6] (Figure 3, lower structure). However, the completely perpendicular geometry does not explain all of the data. For example, it would suggest that cis- and trans-disubstituted alkenes should have very different reactivities, even in the case of aliphatic substituents, and that trisubstituted olefins should suffer a severe interaction with the macrocycle as well. Neither prediction is borne out by experiment. Therefore, we propose that some rotation of the alkene away from the perpendicular is tolerated (Figure 3, upper structure). This would allow trans-disubstituted and tertiary alkenes to escape serious interactions with the macrocyclic plane (R_4 = H in these cases) but would cause the olefin substituents to point in the direction of the ortho hydrogen atoms or

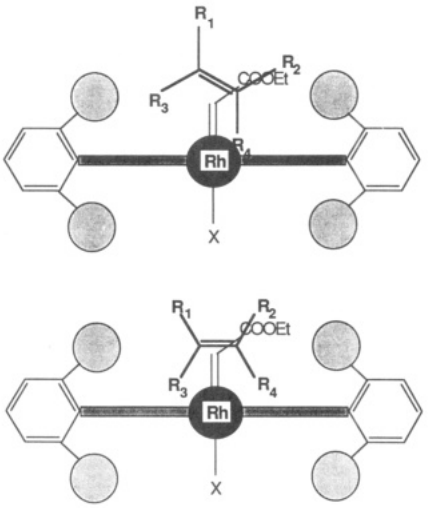


Figure 3. Upper structure: A model for the approach of the alkene to the putative metallocarbene intermediate. This scheme predicts that substrates will suffer severe steric interactions with the catalyst only if they are tetrasubstituted (interaction of R_4 with the macrocycle) or have extremely bulky substituents such as aromatic rings (interaction of R_2 and R_3 with the porphyrin's ortho aryl substituents). Lower structure: Geometry of approach originally proposed for porphyrin-catalyzed cyclopropanations. This arrangement does not adequately rationalize the data in Tables II–IV.

methyl groups of the tetraarylporphyrin, thus explaining the enhanced selectivity of the bulkier RhTMPI catalyst **5** and the much greater selectivity seen in competitions between aryl olefins. Perhaps the most appealing facet of the model is that it readily rationalizes the fact that tetrasubstituted alkenes are such poor substrates. If all four positions of the alkene are substituted, there is no way for all of the groups to escape interactions with the porphyrin plane. Thus, the model in Figure 3 (upper structure) allows us to rationalize adequately the results of all of the shape selectivity experiments.

It is worthwhile to emphasize two aspects of this model. First, it has not been shown definitively that the active species in the cyclopropanation reaction is indeed a rhodium carbene, so this part of the proposal must remain tentative. However, Callot has isolated alkylrhodium porphyrins from the reaction of the iodorhodium complex with a diazo compound that are consistent with trapping of the cationic carbene with I^- or added alcohol.[29,31] We have obtained similar results.[32] Efforts are under way in this laboratory to isolate the putative carbene species at low temperature in the absence of nucleophiles. Second, the Figure 3 model does *not* constitute a mechanistic hypothesis but is a geometric model for predictive purposes only. The detailed chemical mechanism of carbene transfer from the porphyrin to the alkene is not clear although the results of recent experiments suggest a concerted transfer.[33] The general arrangement of the atoms in our model is consistent with the transition state of a carbene transfer of the type proposed by Brookhart and co-workers for transfer of ethylidene fragments from $[Cp(CO)(R_3P)FeCHCH_3]^+$ to alkenes.[34,35] It is possible

(31) Callot, H. J. and Schaeffer *J. Chem. Soc., Chem. Commun.* **1978**, 937–938.
(32) Maxwell, J.; Kodadek, T. *Organometallics* **1991**, *10*, 4–6.
(33) Brown, K. C.; Kodadek, T. Manuscript in preparation.
(34) Brookhart, M.; Liu, Y.; Goldman, E. W.; Timmers, D. A.; Williams, G. D. *J. Am. Chem. Soc.* **1991**, *113*, 927–939.
(35) Brookhart, M.; Kegley, S. E.; Husk, G. R. *Organometallics* **1984**, *2*, 650–652.

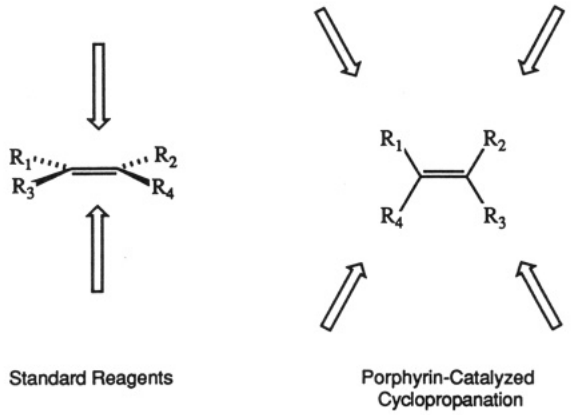


Figure 4. Porphyrin-catalyzed cyclopropanation reaction exhibits an unusual geometry that demands access to the alkene along a vector corresponding to one of the alkene–R bonds (right schematic). This is quite different from typical reagents that approach the alkene from above (left schematic).

that the porphyrin-catalyzed reaction may proceed via a similar mechanism.

The synthetic implications of the data shown in Tables II and III are interesting. In considering the relative accessibility of an alkene to electrophilic attack, one is usually concerned with whether the space above or below the alkene plane is accessible. However, for the present reaction, the shape selectivity data suggest that the relevant question is whether one of the "corners" of the olefin is sufficiently unhindered to allow approach of the putative metallocarbene (Figure 4), an unusual selectivity that might be of utility for the selective cyclopropanation of particular olefins in certain polyenes.

The Figure 3 model suggests that a major deficiency of the chiral wall catalyst is the presence of the relatively unhindered slot between the aromatic walls. If the alkene does indeed approach the active species in a more or less perpendicular manner, examination of models suggests that the substituents will not clash too severely with the naphthyl walls no matter which enantioface of the alkene is oriented toward the metal (Figure 5). If this analysis is correct, the solution would appear to be to add bulky groups to the outer aromatic rings in order to restrict access to the quadrants of the "active site" nearest the aromtic walls (shaded areas in Figure 5). The construction of these second-generation chiral wall porphyrins is under way.

Experimental Section

Chemicals. RhTTPI and RhTMPI catalysts were prepared according to the procedure of Callot.[29] All olefins were filtered through neutral alumina prior to use. Yields were determined on a Hewlett-Packard 5890A gas chromatograph equipped with a 5% SE-30 packed column using octane as the internal standard.

5α,10β,15α,20β-Tetrakis[(*R*)-1,1′-binaphth-2-yl]porphyrin ("Chiral Wall" Porphyrin, 2). A three-necked 500-mL round-bottom flask equipped with a reflux condenser and a fritted glass argon inlet tube was charged with 238 mL of freshly distilled CH_2Cl_2. After argon was bubbled through the solvent for 25 min, (*R*)-binaphthaldehyde[31] (1) was added (1.0 g, 3.5 mmol) followed by sequential addition of pyrrole (0.247 mL, 3.5 mmol; freshly distilled from CaH) and triethylorthoacetate (0.654 mL). The solution was stirred for 15 min, and then 96 μL of a 2.5 M BF_3OEt_2 solution was added. The resulting red solution was shielded from ambient light while the progress of the reaction was checked by oxidizing small aliquots of solution with DDQ and monitoring the Soret at 433 nm in the visible spectrum. When the Soret maintained a maximum absorbance, the solution was immediately oxidized by adding *p*-chloranil (723 mg, 0.75 equiv) and heating the solution to reflux for 1 h. The optimal reaction times varied considerably from run to run: A 9.7% porphyrin yield was obtained in 51 h, and somewhat lower yields have been found with 9- and 16-h reaction times. We suspect that the variability is due to the history of the Lewis acid catalyst. The longer runs required periodic additions of supplementary acid catalyst. The contents of the flask after oxidation were poured into a separatory funnel and the quinone components removed by washing with an aqueous 5% NaOH/5% $Na_2S_2O_4$ solution. The organic layer was dried and concentrated to give a greenish black solid, which was subjected to Soxhlet extraction with MeOH for 24 h and recovered with CH_2Cl_2. The atropisomers were separated by loading approximately 25 mg of solid onto a Florisil flash column (Fluka, 200–300 mesh, 1-cm diameter, 35-cm height). Elution with 7/1 CH_2Cl_2 hexanes gave a large leading green band (non α,β,α,β atropisomers and impurities) followed by a lighter forest green band (α,β,α,β (1); 7.6 mg collected). Characterization data: ^1H NMR (300 MHz, 22 °C) δ 8.580 (s, 4 H, pyrrolic), 8.362 (s, 4 H, pyrrolic), 8.274 (d, 4 H, np H3), 8.186 (dd, 4 H, np H8), 8.134 (d, 4 H, np H4), 7.708 (dd, 4 H, np H5′), 7.624 (ddd, 4 H, np H7), 7.361 (ddd, 4 H, np H6), 7.324 (dd, 4 H, np H8′), 7.209 (ddd, 4 H, np H6′), 7.184 (dd, 4 H, np H5), 7.128 (ddd, 4 H, np H7′), 7.116 (dd, 4 H, np H2′), 6.968 (dd, 4 H, np H4′), 6.470 (dd, 4 H, np H3′), −3.57 (s, 2 H, internal); UV λ_{max} 433 nm ($\epsilon = 3.5 \times 10^5$), 555 ($\epsilon = 4.8 \times 10^3$), 595 ($\epsilon = 5.0 \times 10^3$), 652 ($\epsilon = 2.2 \times 10^3$); MW ($C_{100}H_{62}H_4$) 1320.

Iodo(5α,10β,15α,20β-tetrakis[(*R*)-1,1′-binaphth-2-yl]-porphyrinato)rhodium(III) (3) was prepared according to literature procedure.[32] RhTBNPI: UV λ_{max} 435 nm ($\epsilon = 1.12 \times 10^5$), 281 ($\epsilon = 4.87 \times 10^4$), 536 ($\epsilon = 1.72 \times 10^4$); MW ($C_{100}H_{60}N_4RhI$) 1548.

Enantioselective Cyclopropanations with RhTBNPI. RhTBNPI catalyst (3.6×10^{-3} mmol), olefin (20 mmol), CH_2Cl_2 (500 mL), and octane (GC standard, 5 mmol) were combined in a 10-mL round-bottom flask equipped with an N_2 collector and a room-temperature water bath. Ethyl diazoacetate (5 mmol) was added and the reaction progress monitored by GC. When the rate of product formation stopped, additional EDA was added (to a total of 20 mmol). Workup consisted of a vacuum distillation and/or a flash column on silica (3/1 hexanes ether). The products of the *cis*-β-methylstyrene and allylbenzene reactions were analyzed as a mixture of syn and anti isomers.

Analysis of the Asymmetric Induction. Chiral shift NMR experiments were performed using approximately 15 mg of cyclopropyl esters with the chiral shift reagent tris[3-((heptafluoropropyl)hydroxymethylene)-(+)-camphorato]europium(III) on a 300-MHz GE spectrometer. With the exception of sty-

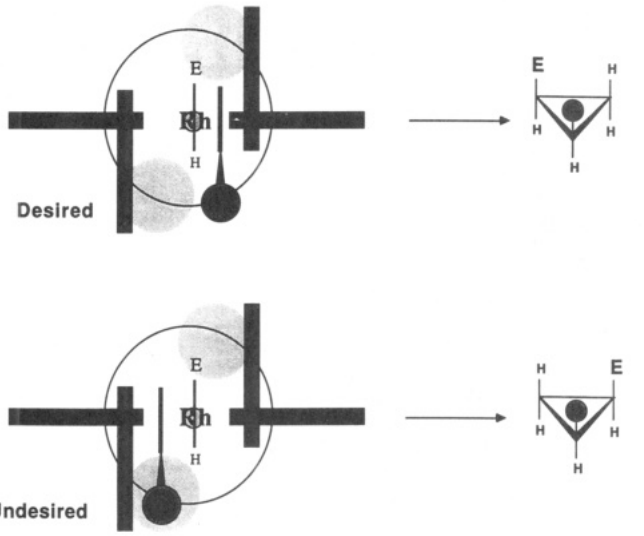


Figure 5. Proposed geometry for the interaction of a generic monosubstituted alkene with the putative rhodium carbene intermediate in the asymmetric cyclopropanation reactions catalyzed by the chiral wall derivative **3**. In this view, the current construct suffers from insufficient steric bulk in the "slot" defined by the naphthyl walls to efficiently restrict the substrate from approaching in the undesired geometry. We propose that attaching bulky substituents to the outer aromatic rings (shaded areas) will enforce the desired enantifacial approach of the substrate to the active intermediate.

rene-derived cyclopropyl esters, the syn and anti forms proved to be inseparable, thus frustrating any attempts to determine the absolute configurations of the products. However, because of the chemical shift dispersion of key signals for the diastereomers, the NMR shift experiment could be carried out successfully on the mixtures to determine enantiomeric excess (ee) values.

Ethyl *syn*-3-methyl-*syn*-2-phenylcyclopropanecarboxylate (*cis*-β-methylstyrene product): ^{1}H NMR ($CDCl_3$, 300 MHz) δ 7.32–7.15 (5 H), 4.05 (q, 2 H), 2.63 (t, 1 H), 2.06 (t, 1 H), 1.76 (m, 1 H), 1.30 (d, 3 H), 1.18 (t, 3 H).

Ethyl *anti*-3-methyl-*anti*-2-phenylcyclopropanecarboxylate (*cis*-β-methylstyrene product): ^{1}H NMR ($CDCl_3$, 300 MHz) δ 7.32–7.15 (5 H, 4.14 (q, 2 H), 2.75 (dd, 1 H), 2.82 (m, 1 H), 2.71 (m, 1 H), 1.29 (t, 3 H), 0.89 (d, 3 H).

Ethyl *syn*-2-benzylcyclopropanecarboxylate (allylbenzene product): ^{1}H NMR ($CDCl_3$, 300 MHz) δ 7.35–7.19 (5 H), 4.12 (q, 2 H), 2.93 (dd, 1 H), 2.83 (dd, 1 H), 1.78 (m, 1 H), 1.52 (m, 1 H), 1.23 (t, 3 H), 1.10 (m, 1 H), 0.84 (dd, 1 H).

Ethyl *anti*-2-benzylcyclopropanecarboxylate (allylbenzene product): ^{1}H NMR ($CDCl_3$, 300 MHz) δ 7.35–7.19 (5 H), 4.16 (q, 2 H), 2.76 (dd, 1 H), 2.57 (dd, 1 H), 1.68 (m, 1 H), 1.52 (m, 1 H), 1.23 (t, 3 H), 1.09 (m, 1 H), 0.82 (m, 1 H).

Procedure for Competition Reactions. All reactions were performed at 60 °C unless indicated otherwise. RhTTPI or RhTMPI (1.7×10^{-3} mmol) in CH_2ClCH_2Cl (1 mL) was added to a premixed solution of olefins (5.3 mmol each). Octane (0.53 mmol) was added to the reaction mixture, and the solution was equilibrated to the reaction temperature. EDA (0.53 mmol) was added, and the reaction was continued until nitrogen evolution was no longer observed. Most of the equivalents of EDA that were not accounted for in the cyclopropane products appeared as dimer products. We have subsequently found that this side reaction can be suppressed almost completely by lowering the temperature to 25 °C. The cyclopropane products are stable under the reaction conditions.

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Selective Preparation of Borinic Esters from Grignard Reagents and Selected Trialkoxyboranes

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The reaction of trialkoxyboranes with ethylmagnesium bromide was investigated for the selective alkylation to the symmetrical borinic esters, R_2BOR'. Triisopropoxyborane was found to react cleanly with 2 equiv of the Grignard reagent to form diethylisopropoxyborane at −40 °C. The selectivity of this reaction is largely controlled by the stability of the bromomagnesium diethyldiisopropoxyborate, $MgBr[Et_2B(O^iPr)_2]$. Triisopropoxyborane was found to be the most selective borane examined, yielding symmetrical borinic esters for primary and aryl derivatives with high selectivities. Secondary alkyl groups showed lower selectivities. This reaction has been developed into a general procedure for preparation of diorganylalkoxyboranes from readily available organomagnesium reagents, especially for those containing organic groups which are not accessible via hydroboration.

Recently there has been renewed interest in borinic acids and esters as intermediates for tertiary alcohols,[1,2] ketones,[3,4] α-haloborinic esters,[5] lithium dialkylborohydrides,[6] and new types of dialkylboranes.[7] The utility of these boron compounds has largely been limited by their availability as the pure compounds. A variety of methods have been used to prepare these compounds:[8] conversion of the trialkylboranes to borinic esters by reactions with alcohols[9] or aldehydes[10] and redistribution of the trialkylboranes with trialkoxyboranes[11] or trihaloboranes followed by reaction with an alcohol.[12–14] However, these reactions suffer from some limitations on the preparative scale.[11,13,15] Borinic esters and acids can also be prepared starting with a monohaloborane[16] followed by stepwise hydroboration of the alkyldihaloborane.[17] Generally these methods are limited to those types of organic groups that can be prepared by the hydroboration reaction. The selective stepwise addition of organolithium reagents has presented a simpler synthesis of borinic derivatives, although one is still limited by the availability of the corresponding organolithium reagents.[18] Grignard reagents are more easily prepared, and their use would considerably simplify the preparation of borinic esters. The synthesis of borinic acids, anhydrides, and esters from the Grignard reagents was explored sometime ago. The majority of these products were diarylborinic derivatives.[19–21] These air-

(1) Junchai, B.; Weike, Z.; Hongxun, D. *J. Organomet. Chem.* **1989**, *367*, C9.
(2) Brown, H. C.; Lane, C. *Synthesis* **1972**, 303.
(3) Brown, H. C.; Jadhav, P. K.; Desai, M. C. *Tetrahedron* **1984**, *40*, 1325.
(4) Brown, H. C.; Srebnik, M.; Bakshi, R. K.; Cole, T. E. *J. Am. Chem. Soc.* **1987**, *109*, 5420.
(5) Carlson, B. A.; Katz, J. J.; Brown, H. C. *J. Organomet. Chem.* **1974**, *67*, C39.
(6) Singaram, B.; Cole, T. E.; Brown, H. C. *Organometallics* **1984**, *3*, 1520.
(7) Cole, T. E.; Bakshi, R. K.; Srebnik, M.; Singaram, B.; Brown, H. C. *Organometallics* **1986**, *5*, 2303.
(8) The older literature is well reviewed: Lappert, M. F. *Chem. Rev.* **1956**, *56*, 959.
(9) Johnson, J. R.; Van Campen, M. G. *J. Am. Chem. Soc.* **1938**, *60*, 121.
(10) Meerwein, H.; Hinz, G.; Majert, H.; Sonke, H. *J. Prakt. Chem.* **1937**, *147*, 226.
(11) Brown, H. C.; Gupta, S. K. *J. Am. Chem. Soc.* **1971**, *93*, 2802.
(12) Buls, V. W.; Davis, O. L.; Thomas, R. I. *J. Am. Chem. Soc.* **1957**, *79*, 337.
(13) Köster, R.; Grassberger, M. A. *Liebigs Ann. Chem.* **1968**, *719*, 169.
(14) Brown, H. C.; Basavaiah, D.; Bhat, N. G. *Organometallics* **1983**, *2*, 1309.
(15) McCusker, P. A.; Hennion, G. F.; Ashby, E. C. *J. Am. Chem. Soc.* **1957**, *79*, 5192.
(16) Brown, H. C.; Ravindran, N. *J. Am. Chem. Soc.* **1972**, *94*, 2112.
(17) Kulkarni, S. U.; Basavaiah, D.; Zaidlewicz, M.; Brown, H. C. *Organometallics* **1982**, *1*, 212.
(18) Brown, H. C.; Cole, T. E.; Srebnik, M. *Organometallics* **1985**, *4*, 1788.

0276-7333/92/2311-0652$03.00/0