JOC Article

Diastereoselective and Enantioselective Cyclopropanation of Alkenes Catalyzed by Cobalt Porphyrins

Lingyu Huang, Ying Chen, Guang-Yao Gao, and X. Peter Zhang*

Department of Chemistry, University of Tennessee, Knoxville, Tennessee 37996-1600

pzhang@utk.edu

Received July 25, 2003

Cobalt(II) porphyrin complexes were shown to be general and efficient catalysts for selective cyclopropanation of alkenes with ethyl diazoacetate (EDA). The catalytic system can operate with alkenes as limiting reagents, requiring only stoichiometric amounts of EDA. The protocol is performed in one-pot fashion without the need of slow addition of EDA. The diastereoselectivity of the current system can be tuned by using different porphyrin ligands or additives, giving either trans- or cis-dominant cyclopropanes. The asymmetric cyclopropanation was also demonstrated with the use of chiral cobalt porphyrin complexes.

Introduction

Transition metal complex-mediated cyclopropanation of alkenes with diazo compounds is one of the most attractive methods for the efficient and selective construction of synthetically and biologically important cyclopropanes.[1] Among the wide variety of catalytic systems,[2] metalloporphyrin-based systems are unique owing to their excellent selectivity and high catalyst turnover, along with their biological relevance.[3] It was first used in this capacity by Callot with rhodium porphyrins,[4] which was later significantly expanded by Kodadek.[5] Woo showed osmium porphyrins can also catalyze cyclopropanation of alkenes, although with less efficiency.[6] Subsequently, Kodadek and Woo reported that iron porphyrins are active catalysts for shape-selective and stereoselective cyclopropanation of alkenes.[7] More recently, the asymmetric cyclopropanation catalytic activities of ruthenium porphyrins were disclosed by Che et al.,[8] Simonneaux et al.,[9] Berkessel and Frauenkron,[10] and Gross et al.[11]

We recently reported that cobalt porphyrins along with iron and ruthenium porphyrins can catalyze selective olefination of aldehydes and ketones with diazo reagents in the presence of triphenylphosphine.[12] In the light of its possible mechanism that is associated with carbene transfer from cobalt porphyrin to triphenylphosphine, we became interested in exploring the possibility that cobalt porphyrins may also catalyze cyclopropanation.[13,14] We reveal herein that cobalt porphyrins are indeed efficient and general catalysts for diastereoselective and asymmetric cyclopropanation of a variety of olefins (Scheme 1). The reactions can be performed in one-pot fashion

* Corresponding author. Fax: 865-974-3454.

(1) (a) Donaldson, W. A. *Tetrahedron* **2001**, *57*, 8589. (b) Doyle, M. P.; Ren, T. *Prog. Inorg. Chem.* **2001**, *49*, 113. (c) Doyle, M. P.; Protopopova, M. N. *Tetrahedron* **1998**, *54*, 7919. (d) Doyle, M. P.; Forbes, D. C. *Chem. Rev.* **1998**, *98*, 911. (e) Ye, T.; McKervey, M. A. *Chem. Rev.* **1994**, *94*, 1091. (f) Padwa, A.; Krumpe, K. E. *Tetrahedron* **1992**, *48*, 5385−5453. (g) Salaun, J. *Chem. Rev.* **1989**, *89*, 1247.

(2) (a) Lebel, H.; Marcoux, J.-F.; Molinaro, C.; Charette, A. B. *Chem. Rev.* **2003**, *103*, 977. (b) Davies, H. M. L.; Antoulinakis, E. G. *Org. Reactions* **2001**, *57*, 1. (c) Doyle, M. P.; McKervey, M. A.; Ye, T. *Modern Catalytic Methods for Organic Synthesis with Diazo Compounds: From Cyclopropanes to Ylides*; John Wiley & Sons: New York, 1998.

(3) (a) Simonneaux, G.; Le Maux, P. *Coord. Chem. Rev.* **2002**, *228*, 43. (b) Che, C. M.; Huang, J. S. *Coord. Chem. Rev.* **2002**, *231*, 151. (c) Artaud, I.; Gregoire, N.; Leduc, P.; Mansuy, D. *J. Am. Chem. Soc.* **1990**, *112*, 6899. (d) Groves, J. T.; Avarianeisser, G. E.; Fish, K. M.; Imachi, M.; Kuczkowski, R. L. *J. Am. Chem. Soc.* **1986**, *108*, 3837. (e) Mansuy, D. *Pure Appl. Chem.* **1980**, *52*, 681.

(4) (a) Callot, H. J.; Piechocki, C. *Tetrahedron Lett.* **1980**, *21*, 3489. (b) Callot, H. J.; Metz, F.; Piechocki, C. *Tetrahedron* **1982**, *38*, 2365.

(5) (a) Bartley, D. W.; Kodadek, T. *J. Am. Chem. Soc.* **1993**, *115*, 1656. (b) Maxwell, J. L.; Brown, K. C.; Bartley, D. W.; Kodadek, T. *Science* **1992**, *256*, 1544. (c) Brown, K. C.; Kodadek, T. *J. Am. Chem. Soc.* **1992**, *114*, 8336. (d) O'Malley, S.; Kodadek, T. *Organometallics* **1992**, *11*, 2299. (e) Maxwell, J. L.; O'Malley, S.; Brown, K. C.; Kodadek, T. *Organometallics* **1992**, *11*, 645. (f) Maxwell, J. L.; Kodadek, T. *Organometallics* **1991**, *10*, 4. (g) O'Malley, S.; Kodadek, T. *Tetrahedron Lett.* **1991**, *32*, 2445.

(6) (a) Smith, D. A.; Reynolds, D. N.; Woo, L. K. *J. Am. Chem. Soc.* **1993**, *115*, 2511. (b) Djukic, J.-P.; Young, V. G., Jr.; Woo, L. K. *Organometallics* **1994**, *13*, 3995. (c) Hamaker, C. G.; Djukic, J. P.; Smith, D. A.; Woo, L. K. *Organometallics* **2001**, *20*, 5189. (d) Li, Y.; Huang, J.-S.; Zhou, Z.-Y.; Che, C.-M. *J. Am. Chem. Soc.* **2001**, *123*, 4843. (e) Du, G.; Andrioletti, B.; Rose, E.; Woo, L. K. *Organometallics* **2002**, *21*, 4490.

(7) (a) Wolf, J. R.; Hamaker, C. G.; Djukic, J. P.; Kodadek, T.; Woo, L. K. *J. Am. Chem. Soc.* **1995**, *117*, 9194. (b) Aggarwal, V. K.; de Vicente, J.; Bonnert, R. V. *Org. Lett.* **2001**, *3*, 2785. (c) Hamaker, C. G.; Mirafzal, G. A.; Woo, L. K. *Organometallics* **2001**, *20*, 5171. (d) Li, Y.; Huang, J.-S.; Zhou, Z.-Y.; Che, C. M.; You, X.-Z. *J. Am. Chem. Soc.* **2002**, *124*, 13185.

(8) (a) Lo, W. C.; Che, C. M.; Cheng, K. F.; Mak, T. C. W. *Chem. Commun.* **1997**, 1205. (b) Che, C. M.; Huang, J.-S.; Lee, F.-W.; Li, Y.; Lai, T.-S.; Kwong, H.-L.; Teng, P.-F.; Lee, W.-S.; Lo, W.-C.; Peng, S.-M.; Zhou, Z.-Y. *J. Am. Chem. Soc.* **2001**, *123*, 4119. (b) Teng, P.-F.; Lai, T.-S.; Kwong, H.-L.; Che, C. M. *Tetrahedron: Asymmetry* **2003**, *14*, 837.

(9) (a) Galardon, E.; LeMaux, P.; Simonneaux, G. *Chem. Commun.* **1997**, 927. (b) Galardon, E.; Roue, S.; Le Maux, P.; Simonneaux, G. *Tetrahedron Lett.* **1998**, *39*, 2333. (c) Paul-Roth, C.; Montigny, F. D.; Rethore, G.; Simonneaux, G.; Gulea, M.; Masson, S. *J. Mol. Catal. A: Chem.* **2003**, *201*, 79.

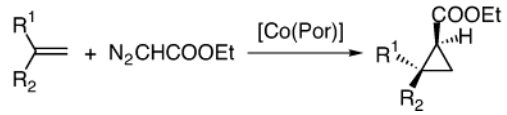
(10) Frauenkron, M.; Berkessel, A. *Tetrahedron Lett.* **1997**, *38*, 7175.

(11) Gross, Z.; Galili, N.; Simkhovich, L. *Tetrahedron Lett.* **1999**, *40*, 1571.

(12) (a) Chen, Y.; Huang, L.; Ranade, M. A.; Zhang, X. P. *J. Org. Chem.* **2003**, *68*, 3714. (b) Chen, Y.; Huang, L.; Zhang, X. P. *J. Org. Chem.* **2003**, *68*, 5925. (c) Chen, Y.; Huang, L.; Zhang, X. P. *Org. Lett.* **2003**, *5*, 2493.

10.1021/jo035088o CCC: $25.00
Published on Web 09/24/2003

SCHEME 1. Cyclopropanation of Alkenes Catalyzed by Cobalt Porphyrins



without the need of slow addition of diazo compounds and with alkenes as limiting reagents, a practical protocol that is atypical for previously reported metalloporphyrin systems. Under these practical conditions, we showed that cobalt porphyrins are superior catalysts in comparison with iron, ruthenium, and rhodium porphyrins, as the common dimerization side reaction was minimized within the cobalt system. In addition, we demonstrated that the diastereoselectivity of the current system can be tuned by use of different porphyrin ligands or by addition of certain additives, giving either trans- or cis-dominant cyclopropanes.

Results and Discussion

We first investigated the catalytic activity of the cobalt complex of *meso*-tetraphenylporphyrin [Co(TPP)] using styrene as a model substrate. The reactions were typically carried out for 1 h at 80 °C in toluene or at room temperature in dichloromethane with 1.2 equiv of EDA using 2 mol % Co(TPP) per 1.0 equiv of styrene. As a comparison, the same reactions were also carried out with Fe(TPP)Cl, Ru(TPP)(CO), and Rh(TPP)I. As indicated in Table 1, Co(TPP) not only catalyzed the reaction, but also afforded the desired product with the highest conversion at room temperature (Table 1, entry 7) and at 80 °C (Table 1, entry 8), though Ru(TPP)(CO) gave the best trans-selectivity (Table 1, entries 3 and 4). The best catalytic activity of Co(TPP) is clearly attributed to its lowest production of the common dimerization products: ethyl maleate and fumarate (Table 1). For example, the ratios of sm:dm:cp (starting material:dimerization products:cyclopropanation product) at 80 °C were 2:1:97, 28:20:52, 33:31:36, and 48:34:18 in Co(TPP), Rh(TPP)I, Fe(TPP)Cl, and Ru(TPP)(CO) system, respectively (Table 1, entries 8, 6, 2, and 4). The same trend of the sm:dm:cp ratios was observed at room temperature: 20:7:73, 28:17:55, 28:30:42, and 46:38:16 in the Co(TPP), Rh(TPP)I, Fe(TPP)Cl, and Ru(TPP)(CO) system, respectively (Table 1, entries 7, 5, 1, and 3).

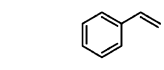
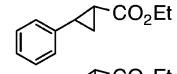
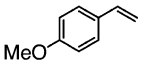
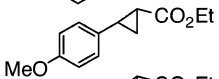
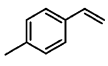
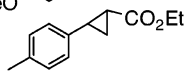
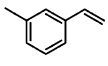
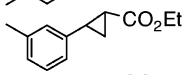
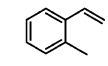
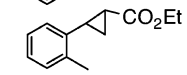
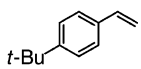
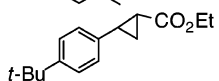
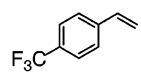
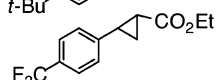
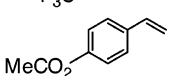
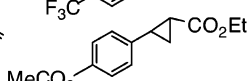
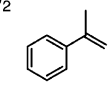
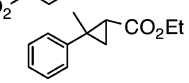
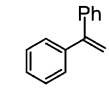
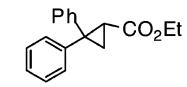
The scope of the cyclopropanation reactions by Co(TPP) was further explored with a variety of alkenes. The results of a series of styrene derivatives are summarized in Table 2. Under the aforementioned typical catalytic conditions, styrene was cyclopropanated with EDA to give the desired product in 93% yield with a cis:trans ratio of 29:71 (Table 2, entry 1). Styrene derivatives having a methyl group in para-, meta-, and ortho-positions (Table 2, entries 3−5) and a *p*-*tert*-butyl group (Table 2, entry 6) are also suitable substrates. Both electron-rich (Table 2, entry 2) and electron-poor (Table 2, entry 7) styrenes could be successfully converted to the desired cyclopropanes in excellent yields. The catalytic conditions could tolerate functional groups such as an acetoxy substituent (Table 2, entry 8). In addition, α-substituted styrenes

TABLE 1. Cyclopropanation of Styrene with EDA Catalyzed by Metal Complexes of *meso*-Tetraphenylporphyrin[a]

entry	[M(TPP]	temp (°C)	sm:dm:cp[b]	cis:trans[b]
1	Fe(TPP)Cl	23	28:30:42	12:88
2	Fe(TPP)Cl	80	33:31:36	14:86
3	Ru(TPP)(CO)	23	46:38:16	06:94
4	Ru(TPP)(CO)	80	48:34:18	05:95
5	Rh(TPP)I	23	28:17:55	36:64
6	Rh(TPP)I	80	28:20:52	36:64
7	Co(TPP)	23	20:07:73	25:75
8	Co(TPP)	80	02:01:97	30:70

[a] Reactions were carried out in toluene for 1 h under N_2 with 1.0 equiv of styrene, 1.2 equiv of EDA, and 2 mol % [M(TPP)]. Concentration: 0.5 mmol styrene/2 mL toluene. [b] sm, starting material styrene; dm, dimerization products of EDA; cp, cyclopropanation product. The ratio was determined by GC.

TABLE 2. Alkene Cyclopropanation with EDA Catalyzed by Co(TPP)[a]

entry	substrate	product	yield (%)[b]	*cis*:*trans*[c]
1			93	29:71
2			92	29:71
3			96	27:73
4			90	26:74
5			89	29:71
6			91	28:72
7			96	23:77
8			99	27:73
9			93	30:70
10			98	- -

[a] Reactions were carried out at 80 °C in toluene for 1 h under N_2 with 1.0 equiv of alkene, 1.2 equiv of EDA, and 2 mol %. Co(TPP). Concentration: 0.5 mmol alkene/2 mL toluene. [b] Yields represent isolated yields of >95% purity as determined by GC and ^{1}H NMR. [c] The ratio was determined by GC or ^{1}H NMR.

(13) For (salen)cobalt-catalyzed cyclopropanation, see: (a) Saha, B.; Uchida, T.; Katsuki, T. *Tetrahedron: Asymmetry* **2003**, *14*, 823. (b) Niimi, T.; Uchida, T.; Irie, R.; Katsuki, T. *Adv. Synth. Catal.* **2001**, *343*, 79. (c) Uchida, T.; Saha, B.; Katsuki, T. *Tetrahedron Lett.* **2001**, *42*, 2521. (d) Niimi, T.; Uchida, T.; Irie, R.; Katsuki, T. *Tetrahedron Lett.* **2000**, *41*, 3647 (e) Ito, Y. N.; Katsuki, T. *Bull. Chem. Soc. Jpn.* **1999**, *72*, 603. (f) Fukuda, T.; Katsuki, T. *Tetrahedron* **1997**, *53*, 7201. (g) Fukuda, T.; Katsuki, T. *Synlett* **1995**, 825. (h) Nakamura, A.; Konishi, A.; Tatsuno, Y.; Otsuka, S. *J. Am. Chem. Soc.* **1978**, *100*, 3443. (i) Nakamura, A.; Konishi, A.; Tsujitani, R.; Kudo, M.; Otsuka, S. *J. Am. Chem. Soc.* **1978**, *100*, 3449.

(14) For 3-oxobutylideneaminatocobalt-catalyzed cyclopropanation, see: (a) Ikeno, T.; Iwakura, I.; Yabushita, S.; Yamada, T. *Org. Lett.* **2002**, *4*, 517. (b) Ikeno, T.; Sato, M.; Sekino, H.; Nishizuka, A.; Yamada, T. *Bull. Chem. Soc. Jpn.* **2001**, *74*, 2139. (c) Ikeno, T.; Iwakura, I.; Yamada, T. *Bull. Chem. Soc. Jpn.* **2001**, *74*, 2151. (d) Ikeno, T.; Nishizuka, A.; Sato, M.; Yamada, T. *Synlett* **2001**, 406. (e) Yamada, T.; Ikeno, T.; Sekino, H.; Sato, M. *Chem. Lett.* **1999**, 719. (f) Ikeno, T.; Sato, M.; Yamada, T. *Chem. Lett.* **1999**, 1345.

TABLE 3. Effect of Additives on Diastereoselectivity of Cyclopropanation of Styrene with EDA Catalyzed by Co(TPP)[a]

entry	additive	equiv	sm:dm:cp[b]	cis:trans[b]
1	pyridine	neat	03:00:97	15:85
2	pyridine	1.0	25:00:75	21:79
3	*N*-methylimidazole	neat	09:00:91	08:92
4	*N*-methylimidazole	1.0	14:00:86	12:88
5	*N*-methylimidazole	0.1	09:00:81	15:85
6	*N*-methylimidazole	0.04	05:00:95	22:78

[a] Reactions were carried out at 80 °C in toluene for 1 h under N_2 with 1.0 equiv of styrene, 1.2 equiv of EDA, and 2 mol %. Co(TPP). Concentration: 0.5 mmol styrene/2 mL toluene. [b] sm, starting material styrene; dm, dimerization products of EDA; cp, cyclopropanation product. The ratio was determined by GC.

TABLE 4. Effect of Porphyrin Ligands on Diastereoselectivity of Cyclopropanation of 4-Methoxystyrene with EDA[a]

entry	[M(TPP]	temp (°C)	sm:dm:cp[b]	cis:trans[b]
1	Co(TMeOPP)	100	00:01:99	31:69
2	Co(TMP)	80	22:08:70	34:66
3	Co(OEP)	80	00:02:98	36:64
4	Co(TDClPP)	80	00:02:98	38:62
5	Co(TPFPP)	80	04:02:94	44:56

[a] Reactions were carried out at 80 °C in toluene for 10 h under N_2 with 1.0 equiv of 4-methoxystyrene, 1.2 equiv of EDA and 2 mol %. Co(TPP). Concentration: 0.5 mmol 4-methoxystyrene/2 mL toluene. [b] sm, starting material 4-methoxystyrene; dm, dimerization products of EDA; cp, cyclopropanation product. The ratio was determined by GC.

could be efficiently transformed to the desired trisubstitued cyclopropane esters (Table 2, entries 9 and 10). In all these cases, excellent yields were obtained with good trans-selectivity.

The trans-diastereoselectivity can be improved with the use of potentially coordinating nitrogen ligands (Table 3). For example, 79% trans-selectivity was obtained when the reaction of styrene with EDA was performed in the presence of 1.0 equiv of pyridine. Better improvements were observed when *N*-methylimidazole was used in as little as 0.04 equiv. The best result was obtained when *N*-methylimidazole was employed as the solvent, achieving 92% trans-selectivity. The diastereoselectivity can also be tuned toward increasing amount of cis-isomer by applying cobalt complexes of different porphyrin ligands including Co(TMeOPP), Co(TMP), Co(OEP), Co(TDClPP), and Co(TPFPP) (Table 4).[15] As illustrated in the case of 4-methoxystyrene, the product cis:trans ratio was gradually increased from 29:71 by Co(TPP) (Table 2, entry 2) to 44:56 by Co(TPFPP) (Table 4, entry 5), although the differences in diasteroselectivity among other cobalt porphyrins are not significant (Table 4).

Our preliminary results (Table 5) indicated that the asymmetric version of the current system could also be achieved by using chiral cobalt porphyrins **A** and **B** (Figure 1), which were prepared by following published methods.[16−19] For example, when styrene was used, the cobalt complex of the homochiral porphyrin **B** afforded the desired product in near same amounts of cis- and trans-isomers (cis:trans = 48:52). The enantioselectivities

(15) TMeOPP, tetra(4-methoxphenyl)porphyrin; TMP, tetra(mesityl)-porphyrin; OEP, octaethylporphyrin; TDClPP, tetra(2,6-dichlorophenyl)-porphyrin; TPFPP, tetra(pentafluorophenyl)porphyrin.

TABLE 5. Asymmetric Cyclopropanation of Styrene with EDA Catalyzed by Chiral Cobalt Porphyrin Complexes[a]

				% ee[c]	
entry	catalyst	yield (%)[b]	cis:trans[b]	cis	trans
1	**A**	73	64:36	77	62
2	**B**	84	48:52	31	10

[a] Reactions were carried out at 80 °C in toluene for 12 h under N_2 with 1.0 equiv of styrene, 1.2 equiv of EDA, and 2 mol % [Co(Por*)]. Concentration: 0.5 mmol styrene/2 mL toluene. [b] The yields and the ratios of cis:trans isomers were determined by GC. [c] The ee was determined by chiral GC.

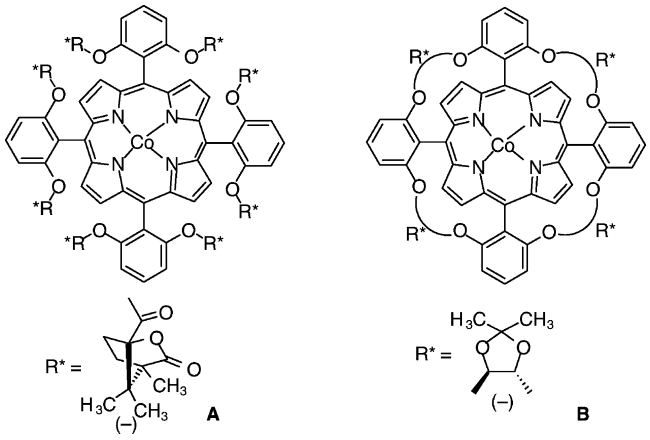


FIGURE 1. Structures of Fe(TPP)Cl and Ru(TPP)(CO).

are 31% ee and 10% ee for *cis*- and *trans*-cyclopropane, respectively (Table 5, entry 2). When the same reaction was catalyzed by the chiral camphanic acid-based porphyrin **A**, it gave a cis-dominant product (cis:trans = 64:36) with enantioselectivities of 77% ee and 62% ee for *cis*- and *trans*-cyclopropane, respectively (Table 5, entry 1).

The catalytic cyclopropanation by cobalt porphyrins are assumed to proceed via a similar mechanism to that which was proposed for other metalloporphyrin systems.[3−11] As shown in Scheme 2, reaction of cobalt(II) porphyrin with EDA generates the cobalt−carbene intermediate **A** with simultaneous release of nitrogen. Carbene transfer from intermediate **A** to alkene substrate affords the cyclopropane product and regenerates cobalt(II) porphyrin, which continues the catalytic cycle. Efforts were made to elucidate the nature of intermediate **A** through NMR and X-ray crystallographic studies. Several intermediates were observed by ^1H and ^{13}C NMR when Co(TPP) was reacted with excess EDA in the

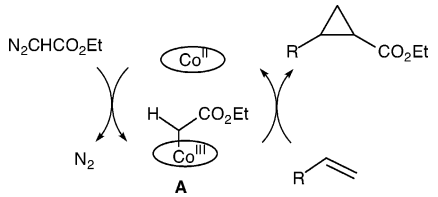
(16) (a) Lindsey, J. S.; Schreiman, I. C.; Hsu, H. C.; Kearney, P. C.; Marguerettaz, A. M. *J. Org. Chem.* **1987**, *52*, 827. (b) Wagner, R. W.; Lindsey, J. S.; Turowskatyrk, I.; Scheidt, W. R. *Tetrahedron* **1994**, *50*, 11097. (c) Collman, J. P.; Lee, V. J.; Zhang, X. *Inorg. Synth.* **1997**, *31*, 117. (d) Tsuchida, E.; Komatsu, T.; Hasegawa, E.; Nishide, H. *J. Chem. Soc., Dalton Trans.* **1990**, 2713.

(17) (a) Tsuchida, E.; Hasegawa, E.; Komatsu, T.; Nakata, T.; Nishide, H. *Chem. Lett.* **1990**, (3), 389. (b) Tsuchida, E.; Komatsu, T.; Hasegawa, E.; Nishide, H. *J. Chem. Soc., Dalton Trans.* **1990**, 2713. (c) Komatsu, T.; Hasegawa, E.; Nishide, H.; Tsuchida, E. *J. Chem. Soc., Chem. Commun.* **1990**, 66.

(18) (a) Shirazi, A.; Goff, H. M. *Inorg. Chem.* **1982**, *21*, 3420. (b) Adler, A. D.; Longo, F. R.; Varadi, V. *Inorg. Synth.* **1976**, *16*, 213.

(19) (a) Ini, S.; Kapon, M.; Cohen, S.; Gross, Z. *Tetrahedron: Asymmetry* **1996**, *7*, 659. (b) Gross, Z.; Ini, S. *J. Org. Chem.* **1997**, *62*, 5514. (c) Gross, Z.; Ini, S. *Org. Lett.* **1999**, *1*, 2077.

SCHEME 2. Possible Mechanism for Cyclopropanation of Alkenes Catalyzed by Cobalt Porphyrins



absence of an alkene substrate. The complexity and multiplicity of the intermediates, however, prevented definite assignment of the structural nature of intermediate **A**. While several possible structures could be proposed, a cobalt(III)−carbene complex with Co−C single bond and carbon-based radical characters is preferred for intermediate **A** (Scheme 2) in view of a recent result on the cyclopropanation intermediate in other cobalt-based catalytic systems.[20]

Conclusions

In summary, we have revealed that cobalt porphyrins are efficient and general catalysts for diastereoselective and enantioselective cyclopropanation of alkenes. The current catalytic system operates with alkenes as limiting reagents and requires no slow-addition of diazo compounds. Under these practical conditions, we demonstrated that cobalt porphyrins are superior catalysts in comparison with the current known metalloporphyrin catalysts. In combination of its tunable diastereoselectiviy, this new methodology may prove useful in the synthesis of cyclopropanes. We are currently working to expand the scope of this method and to improve its enantioselectivity as well as to understand its mechanism.

Experimental Section

General Considerations. All reactions were carried out in oven-dried glassware using standard Schlenk techniques. Toluene was distilled under nitrogen from sodium benzophenone ketyl. Proton and carbon nuclear magnetic resonance spectra (^{1}H NMR and ^{13}C NMR) were recorded on a 300 MHz spectrometer and referenced with respect to internal TMS standard or residual solvent. Enantioselectivity was measured on a HP 6890 GC system with a Varian CP 7502-Chirasil-Dex CB column. High-resolution mass spectroscopy was performed using an electron impact (EI) ionization technique with a 70 eV electron beam. Thin-layer chromatography was carried out on silica gel 60 F-254 TLC plates.

General Procedures for Cyclopropanation Reaction. A porphyrin complex (2 mol %) was placed in an oven-dried, resealable Schlenk tube. The tube was capped with a Teflon screwcap, evacuated, and back-filled with nitrogen. The screwcap was replaced with a rubber septum, and 1.0 equiv of alkene (0.5 mmol) was added via syringe, followed by solvent (1 mL), 1.2 equiv of EDA and solvent again (1 mL). The tube was purged with nitrogen for 1 min, and its contents were stirred at constant temperature in an oil bath. After a certain time, the resulting mixture was cooled to room temperature and concentrated. The residue was purified by flash silica gel chromatography to give the product.

(20) Ikeno, T.; Iwakura, I.; Yamada, T. *J. Am. Chem. Soc.* **2002**, *124*, 15152.

Ethyl 2-phenylcyclopropane-1-carboxylate[21] was synthesized from styrene. ^{1}H NMR (300 MHz, $CDCl_3$) trans-isomer: δ 7.11−7.33 (m, 5H), 4.19 (q, J = 7.2 Hz, 2H), 2.52 (ddd, J = 9.6, 6.3, 4.5 Hz, 1H), 1.91 (m, 1H), 1.61 (m, 1H), 1.28−1.38 (m, 1H), 1.29 (t, J = 7.2 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$) trans-isomer: δ 173.6, 140.4, 128.7, 126.7, 126.4, 60.9, 26.4, 24.4, 17.3, 14.5. ^{1}H NMR (300 MHz, $CDCl_3$) cis-isomer: δ 7.19−7.28 (m, 5H), 3.88 (q, J = 7.2 Hz, 2H), 2.59 (m, 1H), 2.09 (m, 1H), 1.73 (m, 1H), 1.34 (m, 1H), 0.98 (t, J = 7.2 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$) cis-isomer: δ 171.2, 136.8, 129.6, 128.1, 126.9, 60.4, 25.2, 22.1, 14.3, 11.4. HRMS-EI ([M]$^+$): calcd for $C_{12}H_{14}O_2$ 190.0994, found 190.0990 with an isotope distribution pattern that is the same as the calculated one.

Ethyl 2-(4-methoxyphenyl)cyclopropane-1-carboxylate[22] was synthesized from 4-methoxystyrene. ^{1}H NMR (300 MHz, $CDCl_3$) trans-isomer: δ 7.04 (d, J = 8.7 Hz, 2H), 6.82 (d, J = 8.7 Hz, 2H), 4.17 (q, J = 7.5 Hz, 2H), 3.78 (s, 3H), 2.49 (ddd, J = 9.6, 6.9, 4.5 Hz, 1H), 1.83 (ddd, J = 8.7, 5.4, 4.2 Hz, 1H), 1.56 (ddd, J = 9.6, 5.1, 4.2 Hz, 1H), 1.28 (t, J = 7.2 Hz, 3H), 1.25 (m, 1 H). ^{13}C NMR (75 MHz, $CDCl_3$) trans-isomer: δ 173.5, 158.3, 132.0, 127.3, 113,8, 60.6, 55.2, 25.6, 23.8, 16.7, 14.2. ^{1}H NMR (300 MHz, $CDCl_3$) cis-isomer: δ 7.18 (d, J = 8.1 Hz, 2H), 6.80 (d, J = 8.1 Hz, 2H), 3.89 (q, J = 7.2 Hz, 2H); 3.77 (s, 3H), 2.52 (m, 1H), 2.03 (ddd, J = 9.3, 7.8, 5.4 Hz, 1H), 1.65 (m, 1H), 1.29 (m, 1H), 1.01 (t, J = 7.2 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$) cis-isomer: δ 171.1, 158.3, 130.2, 128.5, 113.3, 60.1, 55.2, 24.8, 21.7, 14.1, 11.2. HRMS-EI ([M]$^+$): calcd for $C_{13}H_{16}O_3$ 220.1099, found 220.1101 with an isotope distribution pattern that is the same as the calculated one.

Ethyl 2-(4-trifluoromethylphenyl)cyclopropane-1-carboxylate[22] was synthesized from 4-trifluoromethylstyrene. ^{1}H NMR (300 MHz, $CDCl_3$) trans-isomer: δ 7.52 (d, J = 8.7 Hz, 2H), 7.19 (d, J = 8.4 Hz, 2H), 4.19 (q, J = 7.2 Hz, 2H), 2.56 (ddd, J = 9.6, 6.3, 3.9 Hz, 1H), 1.95 (ddd, J = 8.7, 5.7, 4.5 Hz, 1H), 1.68 (m, 1H), 1.32 (m, 1H), 1.30 (t, J = 7.2 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$) trans-isomer: δ 172.8, 144.3, 129.6, 126.4, 125.3, 60.9, 25.6, 24.5, 17.2, 12.1. ^{1}H NMR (300 MHz, $CDCl_3$) cis-isomer: δ 7.49 (d, J = 8.4, 2 Hz, 2H), 7.35 (d, J = 7.2 Hz, 2H) 3.86 (q, J = 7.2 Hz, 2H), 2.57 (m, 1H), 2.11 (ddd, J = 9.3, 7.8, 5.4 Hz, 1H), 1.71 (m, 1H), 1.37 (m, 1H), 0.96 (t, J = 7.2 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$) cis-isomer: δ 170.8, 141.0, 129.9, 126.6, 125.0, 60.6, 25.3, 22.2, 14.2, 11.6. HRMS-EI ([M]$^+$): calcd for $C_{13}H_3O_2F_3$ 258.0868, found 258.0873 with an isotope distribution pattern that is the same as the calculated one.

Ethyl 2-(4-acetoxyphenyl)cyclopropane-1-carboxylate[23] was synthesized from 4-acetoxystyrene. ^{1}H NMR (300 MHz, $CDCl_3$) trans-isomer: δ 7.11 (d, J = 9.0 Hz, 2H), 6.99 (d, J = 8.7 Hz, 2H), 4.16 (q, J = 7.2 Hz, 2H), 2.51 (m, 1H), 2.29 (s, 3H), 1.87 (m, 1H), 1.59 (m, 1H), 1.25, (m, 1H), 1.28 (t, J = 7.2 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$) trans-isomer: δ 173.2, 169.6, 149.1, 137.7, 127.2, 121.5, 60.7, 25.6, 24.1, 21.1, 16.9, 14.2. ^{1}H NMR (300 MHz, $CDCl_3$) cis-isomer: δ 7.27 (d, J = 8.7 Hz, 2H), 6.99 (d, J = 8.1 Hz, 2H), 3.88 (q, J = 7.2 Hz, 2H), 2.55 (m, 1H), 2.27 (s, 3H); 2.07 (m, 1H), 1.69 (m, 1H), 1.29 (m, 1H), 0.96 (t, J = 7.2 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$) cis-isomer: δ 170.8, 169.4, 149.2, 134.1, 130.1, 120.9, 60.2, 24.8, 21.8, 21.0, 13.9, 11.3. HRMS-EI ([M]$^+$): calcd for $C_{14}H_{16}O_4$ 248.1049, found 248.1050 with an isotope distribution pattern that is the same as the calculated one.

Ethyl 2-methyl-2-phenylcyclopropane-1-carboxylate[22] was synthesized from α-methylstyrene. ^{1}H NMR (300 MHz, $CDCl_3$) trans-isomer: δ 7.18−7.32 (m, 5H), 4.22 (q, J = 7.2 Hz, 2H), 1.99 (dd, J = 8.5, 6.3 Hz, 1H), 1.55 (s, 3 H), 1.45−1.50 (m, 2H), 1.32 (t, J = 7.2 Hz, 3H). ^{13}C NMR (75 MHz,

(21) (a) Solladié-Cavallo, A.; Isarno, T. *Tetrahedron Lett.* **1999**, *40*, 1579. (b) Sanders, C. J.; Gillespie, K. M.; Scott, P. *Tetrahedron: Asymmetry* **2001**, *12*, 1055. (c) Niimi, T.; Uchida, T.; Irie, R.; Katsuki, T. *Adv. Synth. Catal.* **2001**, *343*, 79.

(22) Bachmann, S.; Mezzetti, A. *Helv. Chim. Acta* **2001**, *84*, 3063.

(23) Kusuyama, Y.; Tokami, K. *Magn. Reson. Chem.* **1992**, *30*, 361.

$CDC1_3$) trans-isomer: δ 172.1, 145.8, 128.4, 127.2, 126.4, 60.4, 30.5, 27.8, 20.7, 19.8, 14.4.^{1}H NMR (300 MHz, $CDC1_3$) cis-isomer: δ 7.18−7.32 (m, 5H), 3.69 (m, J = 4.2 Hz, 2H), 1.92 (dd, J = 7.8, 5.5 Hz, 1H), 1.80 (m, 1H), 1.48 (s, 3H), 1.16 (dd, J = 7.8, 4.5 Hz, 1H), 0.96 (t, J = 7.2 Hz, 3H). ^{13}C NMR (75 MHz, $CDC1_3$) cis-isomer: δ 171.2, 141.8, 128.7, 128.1, 126.6, 60.0, 32.0, 28.5, 28.4, 19.4, 13.9. HRMS-EI ([M]$^+$): calcd for $C_{13}H_{16}O_2$ 204.1150, found 204.1152 with an isotope distribution pattern that is the same as the calculated one.

Ethyl 2-(4-methylphenyl)cyclopropane-1-carboxylate[22] was synthesized from 4-methylstyrene. ^{1}H NMR (300 MHz, $CDC1_3$) trans-isomer: δ 7.11 (d, J = 7.8 Hz, 2H), 7.01 (d, J = 8.1 Hz, 2H), 4.19 (q, J = 7.2 Hz, 2H), 2.51 (ddd, J = 9.3, 6.3, 4.2 Hz, 1H), 2.33 (s, 3H), 1.88 (ddd, J = 8.4, 5.1, 4.2 Hz, 1H), 1.59 (ddd, J = 9.0, 5.4, 4.5 Hz, 1H), 1.26−1.36 (m, 1H), 1.30 (t, J = 7.2 Hz, 3H). ^{13}C NMR (75 MHz, $CDC1_3$) trans-isomer: δ 173.5, 137.0, 136.0, 129.1, 126.0, 60.6, 25.9, 24.0, 20.9, 16.9, 14.2. ^{1}H NMR (300 MHz, $CDC1_3$) cis-isomer: δ 7.18 (d, J = 7.8 Hz, 2H), 7.09 (d, J = 8.1 Hz, 2H), 3.92 (q, J = 7.2 Hz, 2H), 2.56 (m, 1H), 2.32 (s, 3H), 2.07 (ddd, J = 9.3, 7.8, 5.6 Hz, 1H), 1.59 (ddd, J = 9.0, 5.4, 4.5 Hz, 1H), 1.26−1.36 (m, 1H), 1.03 (t, J = 7.2 Hz, 3H). ^{13}C NMR (75 MHz, $CDC1_3$) cis-isomer: δ 171.0, 136.0, 133.4, 129.1, 128.5, 60.6, 25.1, 21.6, 21.0, 14.0, 11.1. HRMS-EI ([M]$^+$): calcd for $C_{13}H_{16}O_2$ 204.1150, found 204.1153 with an isotope distribution pattern that is the same as the calculated one.

Ethyl 2-(2-methylphenyl)cyclopropane-1-carboxylate[22] was synthesized from 2-methylstyrene. ^{1}H NMR (300 MHz, $CDC1_3$) trans-isomer: δ 7.00−7.22 (m, 4H), 4.22 (q, J = 7.2 Hz, 2H), 2.54 (ddd, J = 9.0, 6.6, 4.2 Hz), 2.41 (s, 3H), 1.81 (m, 1H), 1.60 (m, 1H), 1.24−1.40 (m, 1H), 1.32 (t, J = 7.2 Hz, 3H). ^{13}C NMR (75 MHz, $CDC1_3$) trans-isomer: δ 173.8, 137.9, 137.8, 129.8, 126.6, 125.8, 60.6, 24.6, 22.3, 19.5, 15.3, 14.3. ^{1}H NMR (300 MHz, $CDC1_3$) cis-isomer: δ 7.06−7.19 (m, 4H), 3.78 (q, J = 7.2 Hz, 2H), 2.55 (m, 1H), 2.27 (s, 3H), 2.09 (m, 1H), 1.68 (m, 1H), 1.28 (m, 1H), 0.86 (t, J = 7.2 Hz, 3H). ^{13}C NMR (75 MHz, $CDC1_3$) cis-isomer: δ 171.1, 138.0, 134.8, 129.3, 129.0, 126.7, 125.3, 59.9, 24.4, 21.0, 19.3, 13.9, 11.1. HRMS-EI ([M]$^+$): calcd for $C_{13}H_{16}O_2$ 204.1150, found 204.1141 with an isotope distribution pattern that is the same as the calculated one.

Ethyl 2-(3-methylphenyl)cyclopropane-1-carboxylate[24] was synthesized from 3-methylstyrene. ^{1}H NMR (300 MHz, $CDC1_3$) trans-isomer: δ 6.92−7.23 (m, 4H), 4.21 (q, J = 7.2 Hz, 2H), 2.52 (ddd, J = 9.3, 6.3, 4.2 Hz, 1H), 2.36 (s, 3H), 1.93 (ddd, J = 8.4, 5.1, 3.9 Hz, 1H), 1.62 (m, 1H), 1.28−1.39 (m, 1 H), 1.31 (t, J = 7.2 Hz, 3H). ^{13}C NMR (75 MHz, $CDC1_3$) trans-isomer: δ 173.4, 140.0, 138.0, 128.3, 127.2, 126.9, 123.1, 60.6, 26.1, 24.1, 21.3, 17.0, 14.2. ^{1}H NMR (300 MHz, $CDC1_3$) cis-isomer: δ 6.94−7.19 (m, 4 H), 3.93 (q, J = 7.2 Hz, 2H), 2.58 (m, 1H), 2.35 (s, 3H); 2.10 (ddd, J = 9.6, 8.1, 6.0 Hz, 1H), 1.73 (m, 1H), 1.28−1.39 (m, 1H), 1.02 (t, J = 7.2 Hz, 3H). ^{13}C NMR (75 MHz, $CDC1_3$) cis-isomer: δ 171.0, 137.3, 136.4, 130.0, 127.7, 126.2, 60.1, 25.4, 21.6, 14.0, 11.0. HRMS-EI ([M]$^+$): calcd for $C_{13}H_{16}O_2$ 204.1150, found 204.1155 with an isotope distribution pattern that is the same as the calculated one.

Ethyl 2-[4′-(*tert*-butyl)phenyl]cyclopropane-1-carboxylate[22] was synthesized from 4-*tert*-butylstyrene. ^{1}H NMR (300 MHz, $CDC1_3$) trans-isomer: δ 7.34 (d, J = 8.4 Hz, 2H), 7.09 (d, J = 8.1 Hz, 2H), 4.21 (q, J = 7.2 Hz, 2H), 2.54 (ddd, J = 9.0, 6.9, 4.5, 1H), 1.94 (ddd, J = 8.4, 5.1, 4.2 Hz, 1H), 1.63 (m, 1H), 1.34−1.38 (m, 1H), 1.35 (s, 9H), 1.32 (t, J = 7.2, 3 H). ^{13}C NMR (75 MHz, $CDC1_3$) trans-isomer: δ 173.4, 149.3, 137.0, 125.7, 125.3, 60.5, 34.4, 31.3, 25.8, 24.1, 16.9, 14.2. ^{1}H NMR (300 MHz, $CDC1_3$) cis-isomer: δ 7.28 (d, J = 8.1 Hz, 2H), 7.19 (d, J = 8.4 Hz, 2H), 3.86 (AB of ABX_3, J = 7.2, 3.3 Hz, 2H), 2.54 (m, 1H), 2.05 (ddd, J = 9.2, 7.8, 5.7 Hz, 1H), 1.70 (m, 1H), 1.30 (m, 1H), 1.29 (s, 9H), 0.92 (t, J = 7.2 Hz, 3H). ^{13}C NMR (75 MHz, $CDC1_3$) cis-isomer: δ 171.0, 149.3, 133.4, 128.8, 124.7, 60.0, 34.3, 31.2, 25.0, 21.7, 13.8, 11.0. HRMS-EI ([M]$^+$): calcd for $C_{16}H_{22}O_2$ 246.1620, found 246.1610 with an isotope distribution pattern that is the same as the calculated one.

Ethyl 2,2-diphenylcyclopropane-1-carboxylate[21b,22] was synthesized from 1,1-diphenylethylene. ^{1}H NMR ($CDC1_3$): δ 7.10−7.36 (m, 10H), 3.90 (m, 2H); 2.53 (dd, J = 8.4, 6.0 Hz, 1H), 2.16 (dd, J = 5.9, 4.8 Hz, 1H), 1.56 (dd, J = 8.1, 4.8 Hz, 1H), 0.99 (t, J = 7.2 Hz). ^{13}C NMR (75 MHz, $CDC1_3$): δ 170.5, 144.7, 140.1, 129.6, 128.3, 128.2, 127.5, 126.8, 126.4, 60.3, 39.7, 28.9, 20.0, 13.9. HRMS-EI ([M]$^+$): calcd for $C_{18}H_{18}O_2$ 266.1307, found 266.1298 with an isotope distribution pattern that is the same as the calculated one.

Synthesis of 5,10,15,20-tetrakis(2,6-dimethoxyphenyl)-21*H*,23*H*-porphyrin (1).[16] An oven-dried, three-necked, 2-L, round-bottomed flask equipped with a magnetic stirring bar and a gas-dispersion tube was charged with 2,6-dimethoxybenzaldehyde (2.5 g, 0.015 mol), pyrrole (1.04 mL, 0.015 mol), and chloroform (1.5 L). The solution was purged with nitrogen for 15 min. Boron trifluoride diethyl etherate (0.570 mL, 2.16 mmol) was added via syringe and the flask was wrapped with aluminum foil to shield it from light. The solution was stirred under nitrogen atmosphere at room temperature 1.5 h, and 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ) (2.55 g, 0.0112 mol) was added as powder at one time. The flask was then immersed in a 65 °C bath for another 1.5 h and cooled to room temperature, and 10 mL of triethylamine was added to neutralize the excessive acid. The reaction solution was then directly poured on the top of a silica gel column that was packed with dichloromethane. The column was eluted with a mixture of dichloromethane and ethyl acetate (9:1). The fractions containing pure product were pooled and concentrated on a rotary evaporator. The residue was suspended in a small volume of acetone, and the precipitate of product was collected on a funnel and washed with hexanes to afford the title compound as a purple crystal-like solid (1.31 g, 40.8%). ^{1}HNMR ($CDCl_3$, 300 MHz): δ 8.65 (s, 8H), 7.66 (t, J = 8.7 Hz, 4H), 6.94 (d, J = 8.1 Hz, 8H), 3.47 (s, 24H), −2.52 (s, 2H). HRMS-EI ([M$^+$]): calcd for $C_{52}H_{46}N_4O_8$ 854.3316, found 854.3324 with an isotope distribution pattern that is the same as the calculated one.

Synthesis of 5,10,15,20-tetrakis(2,6-dihydroxyphenyl)-21*H*,23*H*-porphyrin (2).[16] A 50-mL, round-bottomed flask equipped with a magnetic stirring bar and a gas-dispersion tube was charged with compound **1** (1.31 g, 1.53 mmol) and anhydrous dichloromethane (25 mL). The solution was purged with nitrogen for 5 min and boron tribromide (5 mL, 0.053 mol) was added via syringe. The solution was stirred gently under nitrogen atmosphere at room temperature for 5 h, and 20 mL of water was added carefully. The mixture was stirred thoroughly for 20 min and transferred to a separatory funnel. The product was extracted with ethyl acetate and concentrated on a rotary evaporator. The residue was suspended in a small volume of acetone and the product was collected on a funnel and washed with hexanes to afford the title compound as purple solid (1.0 g, 88%). ^{1}HNMR ($(CD_3)_2CO$, 300 MHz): δ 8.88 (s, 8H), 8.13 (s, 4H,), 7.48 (t, J = 8.1 Hz, 4H), 6.87 (d, J = 8.1 Hz, 8H), 5.83 (s, 4H), −2.68 (s, 2H). HRMS-EI ([M$^+$]): calcd for $C_{44}H_{30}N_4O_8$ 742.2064, found 742.2043 with an isotope distribution pattern that is the same as the calculated one.

Synthesis of 5,10,15,20-Tetrakis(2′,6′-bis(camphanyloxy)phenyl)-21*H*,23*H*-porphine (3).[17] A solution of (*1S*)−(−)-camphanic chloride (0.8672 g, 20-fold) in dried THF (10 mL) was added dropwise into a solution of **2** (0.1484 g) in dried THF (40 mL) in an ice−water bath under a nitrogen atmosphere. After a solution of *p*-(dimethylamino)pyridine (0.4888 g) in dried THF (10 mL) was added, the reaction mixture was heated under reflux. After 14 h, it was allowed to cool to room temperature and the solvent was removed by rotary evaporation. The residue was extracted with $CHCl_3$. The organic phase was washed with 0.1 N HCl (2×), 5 w% Na_2CO_3 (1×) and water (1×), and dried over anhydrous Na_2SO_4. After concentration, it is subjected to chromatography ($CHCl_3$:MeOH = 30:1) to afford the title compound (0.3765 g, 86%). ^{1}H NMR (300 MHz,

(24) Hixson, S. S.; Franke, L. A.; Gere, J. A.; Xing, Y. D. *J. Am. Chem. Soc.* **1988**, *110*, 3601.

$CDC1_3$): δ 8.93 (br, 8H), 7.95 (t, J = 8.1 Hz, 4H), 7.48 (d, J = 8.1 Hz, 8H), 1.01 (br, 8H), 0.69 (s, 48 H), 0.66 (s, 24H), 0.56 (br, 8H), 0.23 (br, 8H), −0.97 (br, 8H), −3.00 (br s, 2H). ^{13}C NMR (75 MHz, $CDC1_3$): δ 176.3, 165.5, 150.8, 130.8, 128.8, 121.1, 107.9, 89.4, 53.8, 285, 27.5, 16.7, 16.4, 8.8. IR (film, cm^{-1}): 1796. HRMS-EI ($[M + Na]^+$): calcd for $C_{124}H_{126}N_4O_{32}$-Na 2206.8281, found 2206.8277 with an isotope distribution pattern that is the same as the calculated one. LRMS-EI: successive losses of 180 mass units ($C_{10}H_{12}O_3$) were observed.

Synthesis of Cobalt(II) 5,10,15,20-Tetrakis(2′,6′-bis-(camphanyloxy)phenyl)-21*H*,23*H*-porphine (A).[18] A DMF solution (10 mL) of **3** (0.0945 g, 0.043 mmol) was added dropwise into a DMF solution (10 mL) of excess $Co(OAc)_2{\cdot}4H_2O$ under a nitrogen atmosphere. The reaction mixture was refluxed for 14 h. After being cooled to room temperature, concentrated, and dried, the residue was purified by column chromatography (silica gel, CH_2Cl_2) to afford the title compound as a red crystalline solid **(**0.0412 g, 43%). Due to the paramagnetic nature of the cobalt(II) complex, its ^{1}H NMR spectrum is too broad to be assigned with certainty. ^{13}C NMR (75 MHz, $CDC1_3$): δ 178.2, 167.4, 162.6, 139.5, 91.0, 61.6, 54.7, 54.1, 52.5, 36.8, 31.7, 30.6, 30.5, 29.6, 28.9, 16.7, 16.6, 14.2, 9.6. IR (film, cm^{-1}): 1799, 1770. HRMS-EI ($[M - 4C_{10}H_{12}O_3 + Na]^+$): calcd for $C_{84}H_{76}N_4O_{20}CoNa$ 1542.4277, found 1542.4294 with an isotope distribution pattern that is the same as the calculated one. LRMS-EI: successive losses of 180 mass units ($C_{10}H_{12}O_3$) were observed.

Synthesis of 5,10,15,20-tetrakis(2′,6′-bis(2″,3″-*O*-isopropylidene-L-threitol)phenyl)-21*H*,23*H*-porphine (4).[19] Porphyrin **2** (0.086 g, 0.114 mmol) and *trans*-(−)-1,4-di-*O*-tosyl-2,3-O-isopropylidene-L-threitol (0.282 g, 0.6 mmol) were dissolved in 20 mL of dry DMF. The solution was heated to 100 °C under N_2. Solid K_2CO_3 (0.285 g, 2.9 mmol) was then added into the solution. After 18 h at 100 °C, the reaction mixture was cooled, diluted with CH_2Cl_2 (20 mL), washed with water (40 mL), dried over Na_2SO_4, filtered, and concentrated in vacuo. The crude product was then purified by flash chromatography (basic alumina, CH_2Cl_2/EtOAc/Et_3N = 50:49:1) to afford the title compound (0.096 g, 67%). ^{1}H NMR (300 MHz, $CDC1_3$): δ 8.30 (d, J = 4.8 Hz, 4H), 8.16 (d, J = 4.8 Hz, 4H), 7.66 (t, J = 8.1 Hz, 4H), 7.24(d, J = 8.1 Hz, 8H), 4.81 (dd, J = 11.0, 2.4 Hz, 4H), 4.44 (dd, J = 9.3, 2.4 Hz, 4H), 4.36 (t, J = 8.7 Hz, 4H), 4.27 (dd, J = 9.6, 2.0 Hz, 4H), 3.95 (d, J = 8.1 Hz, 4H), 2.83 (d, J = 7.8 Hz, 4H), 1.07 (s, 12H), 0.29 (s, 12H), −1.43 (s, 2H).

Synthesis of Cobalt(II) 5,10,15,20-tetrakis(2′,6′-bis-(2″,3″-*O*-isopropylidene-L-threitol)phenyl)-21*H*,23*H*-porphine (B).[18] Free base porphyrin **4** (0.040 g, 0.032 mmol), 2,6-lutidine (0.011 mL, 0.094 mmol), and anhydrous $CoCl_2$ (0.033 g, 0.254 mmol) were dissolved in dry THF and refluxed under N_2 for 2 h. The resulting mixture was cooled to room temperature and the solvent was evaporated in vacuo. The residue was dissolved in ethyl acetate, washed with water three times, dried over Na_2SO_4, filtered, and concentrated in vacuo. The title compound was obtained in 84% yield (0.035 g). Due to the paramagnetic nature of the cobalt(II) complex, its ^{1}H and ^{13}C NMR spectra were too broad to be assigned with certainty. HRMS-EI ($[M]^+$): calcd for $C_{72}H_{68}CoN_4O_{16}$ 1303.3962, found 1303.3942 with an isotope distribution pattern that is the same as the calculated one.

Acknowledgment. We are grateful for financial support of this work from the UT Department of Chemistry, the UT Center of Excellence for Structural Biology (CESB) and Hereditary Disease Foundation (HDF). We wish to acknowledge Dr. Al Tuinman of UT Mass Spectroscopy Center for assistance with high-resolution mass spectroscopy.

JO035088O