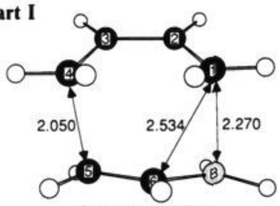
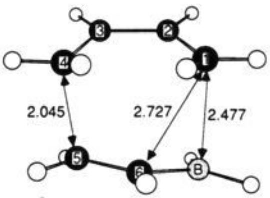
Table I. Absolute and Activation Energies of Transition Structures for Diels–Alder Reactions with Butadiene

	absolute energies (activation energies)		
dienophile	6-31G*//3-21G	6-31*//6-31G*	CASSCF 3-21G
vinylborane, endo	−258.153 502 (35.0)	−258.153 755 (34.9)	−256.781 874
vinylborane, exo	−258.145 864 (39.8)	−258.146 123 (39.7)	
dimethylvinylborane, endo	−336.244 239 (39.0)		−334.455 069
dimethylvinylborane, exo	−336.240 575 (41.3)		

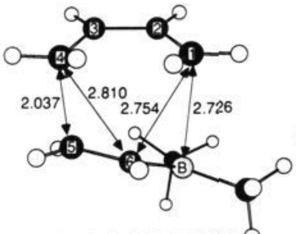
Chart I



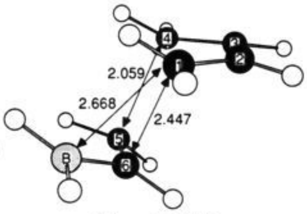
1 (endo, 6-31G*)



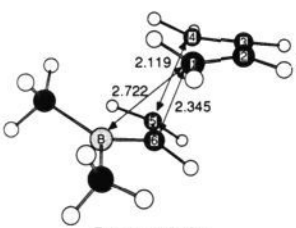
2 (endo, 3-21G CASSCF)



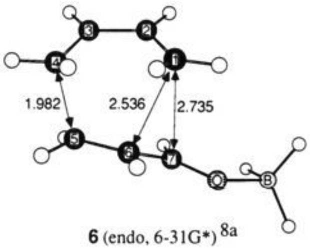
3 (endo, 3-21G CASSCF)



4 (exo, 6-31G*)



5 (exo, 3-21G)

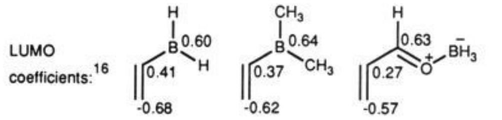


6 (endo, 6-31G*)[8a]

remained as measured by a C_1–B distance of 2.25 Å.

There is little charge separation in these structures. By a Mulliken population analysis in the 6-31G*//3-21G calculations, only 0.06 *e* is transferred to vinyldimethylborane from butadiene. The charges on C_2 and C_3 are unchanged from the starting butadiene (to 0.01 *e*). This is consistent with the striking lack of substituent effects on the rate of these reactions.[1b,d] Despite high asynchronicity, particularly in the CASSCF structures (**2** and **3**), there is little biradical character; using Jensen's definition,[10] the biradical characters for **2** and **3** are only 0.074 and 0.077, respectively.

As with previous ab initio calculations with activated dienophiles,[4,8a,9a] there is no support in these calculations for a Woodward–Hoffman type "secondary orbital interaction"[11] of C_2 with B. However, the bonding interaction of C_1 with B defines a new type of secondary orbital interaction. Notably, this "[4 + 3] interaction" may be discerned in the highest level transition structure calculated by Houk and Birney[8a] for the reaction of butadiene with acrolein·BH_3 (**6**).[12] Although in **6** there is clearly greater interaction of C_1 with C_6 than with the carbonyl carbon C_7, a significant interaction of C_1 with C_7 is suggested by a positive Mulliken overlap population (0.011, this study), a C_1–C_4–C_5–C_6 angle of 17°, and a partial pyramidalization of C_1 toward C_7. No such interaction can be discerned in the corresponding exo transition structures.



A [4 + 3] transition structure can be rationalized from an FMO analysis. Because the largest coefficients of the LUMO of vinylboranes[13] are on the boron and the terminal carbon, the greatest initial overlap of the diene HOMO with the vinylborane LUMO can occur in a [4 + 3] fashion. The LUMO of acrolein·BH_3 is similar. The intriguing dichotomous behavior of endo and exo transition structures in adopting [4 + 3] versus [4 + 2] character is more difficult to understand, but it suggests that [4 + 3] interactions play an important role in the endo selectivity of some Diels–Alder reactions. This will be the subject of a future paper.

Acknowledgment. We thank the NIH, The Robert A. Welch Foundation, and the Texas A&M Supercomputer Center for research support and Ken Houk for a helpful discussion.

Supplementary Material Available: Calculational procedures and final geometries and energies for all calculations (4 pages). Ordering information is available on any current masthead page.

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(10) Jensen, F. *J. Am. Chem. Soc.* **1989**, *111*, 4643.

(11) (a) Woodward, R. B.; Hoffmann, R. *The Conservation of Orbital Symmetry*; Verlag Chemie: Weinheim, Germany, 1970. (b) Houk, K. N. *J. Am. Chem. Soc.* **1973**, *95*, 4092. (c) Houk, K. N.; Strozier, R. W. *J. Am. Chem. Soc.* **1973**, *95*, 4094. (d) Salem, L. *J. Am. Chem. Soc.* **1968**, *90*, 553.

(12) An alternative secondary orbital interaction of C_3 with the oxygen atom of acrolein (see ref 11d) was noted by Houk and Birney in ref 8a for the endo s-cis transition structure. This interaction cannot be present with vinylboranes or s-trans dienophiles.

(13) Program MOPAC QCPE 455. The "outer" components of the LUMO coefficients in ab initio calculations with a 3-21G basis set display a similar trend.

A Cytochrome *c* Oxidase Reactivity Model: Generation of a Peroxo-Bridged Iron/Copper Dinuclear Complex

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Cytochrome *c* oxidase (C*c*O) is a terminal respiratory protein complex which catalyzes the four-electron four-proton reduction of O_2 to water.[1] It possesses an array of metal ion sites, including a dinuclear (porphyrin)iron–copper complex, seen to be critically involved directly in O_2 binding, reduction, and proton pumping. This center consists of a heme a_3 and Cu_B which in the oxidized resting state are strongly spin coupled and EPR silent, with a Cu···Fe distance thought to be less than 5 Å.[1e] The linkage of the O_2-reduction process to proton translocation allows the energy released to be stored as a pH gradient and membrane potential for subsequent ATP synthesis.

Inorganic modeling of this active site dinuclear complex can be very helpful in elucidating aspects of structure, associated spectroscopy, and mechanism of O_2 reduction. Most of the activity associated with such chemistry has been directed at resting-state enzyme models and the generation of mixed-metal iron(III)–Cu(II) complexes having oxo, imidazolato, sulfur-containing, or

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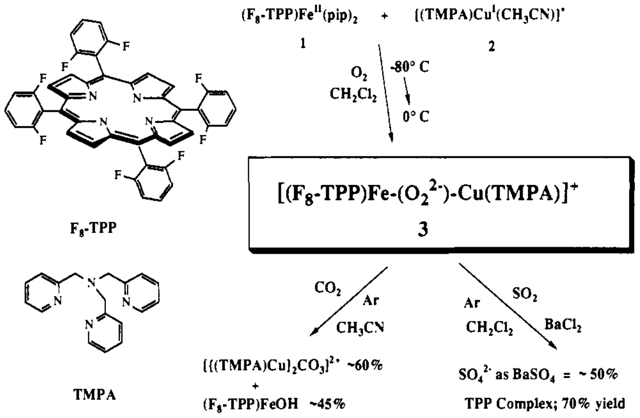
(1) (a) Babcock, G. T.; Wikström, M. *Nature* **1992**, *356*, 301–309 and references cited therein. (b) Chan, S. I.; Li, P. M. *Biochemistry* **1990**, *29*, 1–12. (c) Malmström, B. G. *Chem. Rev.* **1990**, *90*, 1247–1260. (d) Capaldi, R. A. *Annu. Rev. Biochem.* **1990**, *59*, 569–596. (e) Scott, R. A. *Annu. Rev. Biophys. Biophys. Chem.* **1989**, *18*, 137–158.

Scheme I



other bridging ligands.[2,3] Here, we report that exposure of O_2 to (tetraphenylporphyrin)iron(II) complexes and a Cu(I) species leads to the synthesis of a unique set of compounds possessing a peroxo ligand bridging (P)Fe^{III} (P = tetraarylporphyrin) and Cu(II)–ligand moieties.

As part of our ongoing activities in copper dioxygen reactivity,[4,5] we have previously reported the synthesis and structure of $[\{(TMPA)Cu\}_2(O_2)]^{2+}$ (TMPA = tris[2-pyridylmethyl]amine), a *trans*-μ-1,2-O_2^{2-} dicopper(II) complex formed from a mononuclear Cu(I) precursor $[(TMPA)Cu]^+$ (**2**) when reacted with O_2 at −80 °C.[6,7] Initially, we thought to employ a self-assembly approach, reacting **2** and a tetraarylporphyrin–Fe(II) complex (P)Fe-B$_2$ (B = base) with dioxygen; this route has turned out to be very fruitful. Thus, when an equimolar solution of (F$_8$-TPP)Fe-pip$_2$ (**1**) (F$_8$-TPP = tetrakis(2,6-difluorophenyl)porphyrin; pip = piperidine) and $[(TMPA)Cu]^+$ (**2**) is exposed to O_2 in CH_2Cl_2 at −80 °C, a purple-red color develops rapidly. If this is allowed to warm slowly to 0 °C and heptane is added, a purple-red solid formulated as [(F$_8$-TPP)Fe-(O_2^{2-})-Cu(TMPA)]$^+$ (**3**) can be isolated in high yield (>80%) (Scheme I). Reprecipitation from acetonitrile/diethyl ether at room temperature gives **3** as a microcrystalline material in ~50% overall isolated yield.[8] This compound is stable in dry acetonitrile solution at room temperature and indefinitely as a solid. A similar reaction occurs with (TPP)Fe-pip$_2$, but solutions (which are green) and the solid are much less stable.[9]

Formulation of **3** as a peroxo complex $[Fe^{III}\text{-}(O_2^{2-})\text{-}Cu^{II}]^+$ comes from a variety of observations, including manometric measurements demonstrating the stoichiometry of uptake of O_2 by the equimolar mixture of **1** and **2** (e.g., 1.0 ± 0.1 molar equiv of O_2; two trials); a UV–vis spectrum of the resulting solution is identical to that of the isolated material (vide infra). Elemental analyses for both ClO_4^- and PF_6^- salts are satisfactory,[8] and **3** is a 1:1 electrolyte in CH_3CN. Deliberate decomposition of **3** using NH_4OH(aq), followed by extraction into CH_2Cl_2, indicates the presence of equimolar quantities of (F$_8$-TPP)Fe and TMPA, as determined by integration of a ^{1}H NMR spectrum.

The Mössbauer spectroscopic properties of solid $[Fe^{III}\text{-}(O_2^{2-})\text{-}Cu^{II}](ClO_4)$ (**3**-ClO$_4$) are particularly revealing (supplementary material). The 4.2 K zero-field spectrum is a very sharp quadrupole doublet, with fitted parameters $\delta = 0.47 \pm 0.01$ mm/s and $\Delta E_Q = 1.26 \pm 0.02$ mm/s, typical for high-spin Fe(III)-heme ($S = {}^5/_2$). With a parallel applied field of 60 mT, significant broadening is observed. Since mononuclear high-spin porphyrin Fe(III) generally displays magnetic hyperfine structure in its Mössbauer spectra, the observations cited here indicate that the iron in **3** is magnetically coupled to another half-integer spin center (i.e., the Cu(II)), forming an overall nonzero integer spin system. Interestingly, the Mössbauer parameters observed in **3** compare rather closely to values observed for oxidized forms of both beef heart cytochrome *c* oxidase and *Thermus thermophilus* cytochrome c_1aa_3.[10]

Additional physical and chemical characteristics also support the $[Fe^{III}\text{-}(O_2^{2-})\text{-}Cu^{II}]^+$ (**3**) formulation. (1) The UV–vis spectrum of **3** shows a Soret band at 434 nm, a rather low energy value for

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(2) Model compounds containing porphyrin–Fe(III) include the following: (a) Prosperi, T.; Tomlinson, A. A. G. *J. Chem. Soc., Chem. Commun.* **1979**, 196–197. (b) Gunter, M. J.; Mander, L. N.; Mclaughlin, G. M.; Murray, K. S.; Berry, K. J.; Clark, P. E.; Buckingham, D. A. *J. Am. Chem. Soc.* **1980**, *102*, 1470–1473. (c) Berry, K. J.; Clark, P. E.; Gunter, M. J.; Murray, K. S. *Nouv. J. Chim.* **1980**, *4*, 581–585. (d) Gunter, M. J.; Mander, L. N.; Murray, K. S. *J. Chem. Soc., Chem. Commun.* **1981**, 799–801. (e) Gunter, M. J.; Mander, L. N.; Murray, K. S.; Clark, P. E. *J. Am. Chem. Soc.* **1981**, *103*, 6784–6787. (f) Deardorff, E. A.; Carr, P. A. G.; Hurst, J. K. *J. Am. Chem. Soc.* **1981**, *103*, 6611–6616. (g) Lukas, B.; Miller, J. R.; Silver, J.; Wilson, M. T. *J. Chem. Soc., Dalton Trans.* **1982**, 1035–1040. (h) Elliott, C. M.; Akabori, K. *J. Am. Chem. Soc.* **1982**, *104*, 2671–2674. (i) Chang, C. K.; Koo, M. S.; Ward, B. *J. Chem. Soc., Chem. Commun.* **1982**, 716–719. (j) Dessens, S. E.; Merrill, C. L.; Saxton, R. J.; Ilaria, R. L., Jr.; Lindsey, J. W.; Wilson, L. J. *J. Am. Chem. Soc.* **1982**, *104*, 4357–4361. (k) Saxton, R. J.; Olson, L. W.; Wilson, L. J. *J. Chem. Soc., Chem. Commun.* **1982**, 984–986. (l) Schauer, C. K.; Akabori, K.; Elliott, M.; Anderson, O. P. *J. Am. Chem. Soc.* **1984**, *106*, 1127–1128. (m) Gunter, M. J.; Berry, K. J.; Murray, K. S. *J. Am. Chem. Soc.* **1984**, *106*, 4227–4235. (n) Saxton, R. J.; Wilson, L. J. *J. Chem. Soc., Chem. Commun.* **1984**, 359–361. (o) Chunplang, V.; Wilson, L. J. *J. Chem. Soc., Chem. Commun.* **1985**, 1761–1763. (p) Elliott, C. M.; Jain, N. C.; Cranmer, B. K.; Hamburg, A. W. *Inorg. Chem.* **1987**, *26*, 3655–3659. (q) Brewer, C. T.; Brewer, G. A. *Inorg. Chem.* **1987**, *26*, 3420–3422. (r) Serr, B. R.; Headford, C. E. L.; Elliott, C. M.; Anderson, O. P. *J. Chem. Soc., Chem. Commun.* **1988**, 92–94. (s) For an imidazolate-bridged Mn–porphyrin–Cu complex, see: Koch, C. A.; Wang, B.; Brewer, G.; Reed, C. A. *J. Chem. Soc., Chem. Commun.* **1989**, 1754–1755. (t) Koch, C. A.; Reed, C. A.; Brewer, G. A.; Rath, N. P.; Scheidt, W. R.; Gupta, G.; Lang, G. *J. Am. Chem. Soc.* **1989**, *111*, 7645–7648. (u) Serr, B. R.; Headford, C. E. L.; Anderson, O. P.; Elliott, C. M.; Schauer, C. K.; Akabori, K.; Spartalian, K.; Hatfield, W. E.; Rohrs, B. R. *Inorg. Chem.* **1990**, *29*, 2663–2671. (v) Gupta, G. P.; Lang, G.; Koch, C. A.; Wang, B.; Scheidt, W. R.; Reed, C. A. *Inorg. Chem.* **1990**, *29*, 4234–4239. (w) Bulach, V.; Mandon, D.; Weiss, R. *Angew. Chem., Int. Ed. Engl.* **1991**, *30*, 572–575.

(3) Species containing non-porphyrin Fe moieties: (a) Petty, R. H.; Wilson, L. J. *J. Chem. Soc., Chem. Commun.* **1978**, 483–485. (b) Petty, R. H.; Welch, B. R.; Wilson, L. J.; Bottomley, L. A.; Kadish, K. M. *J. Am. Chem. Soc.* **1980**, *102*, 611–620. (c) Kanda, W.; Okawa, H.; Kida, S. *Bull. Chem. Soc. Jpn.* **1984**, *57*, 1159–1160. (d) Brewer, G. A.; Sinn, E. *Inorg. Chem.* **1984**, *23*, 2532–2537. (e) Brewer, G. A.; Sinn, E. *Inorg. Chem.* **1987**, *26*, 1529–1535. (f) Chaudhuri, P.; Winter, M.; Fleischhauer, P.; Haase, W.; Florke, U.; Haupt, H. *J. Chem. Soc., Chem. Commun.* **1990**, 1728–1730. (g) Morgenstern-Badarau, I.; Laroque, D.; Bill, E.; Winkler, H.; Trautwein, A. X.; Robert, F.; Jeannin, Y. *Inorg. Chem.* **1991**, *30*, 3180–3188. (h) Chetcuti, P. A.; Liegard, A.; Rihs, G.; Rist, G. *Helv. Chim. Acta* **1991**, *74*, 1591–1599. (i) Juarez-Garcia, C.; Hendrich, M. P.; Holman, T. R.; Que, L.; Münck, E. *J. Am. Chem. Soc.* **1991**, *113*, 518–525. (j) Borovik, A. S.; Que, L., Jr.; Papaefthymiou, V.; Münck, E.; Taylor, L. F.; Anderson, D. P. *J. Am. Chem. Soc.* **1988**, *110*, 1986–1988.

(4) (a) Tyeklár, Z.; Karlin, K. D. *Acc. Chem. Res.* **1989**, *22*, 241–248. (b) Karlin, K. D.; Tyeklár, Z.; Zuberbühler, A. D. In *Bioinorganic Catalysis*; Reedijk, J., Ed.; Marcel Dekker: New York, in press. (c) Karlin, K. D.; Tyeklár, Z. *Adv. Inorg. Biochem.*, in press.

(5) (a) Sanyal, I.; Strange, R. R.; Blackburn, N. J.; Karlin, K. D. *J. Am. Chem. Soc.* **1991**, *113*, 4692–4693. (b) Karlin, K. D.; Wei, N.; Jung, B.; Kaderli, S.; Zuberbühler, A. D. *J. Am. Chem. Soc.* **1991**, *113*, 5868–5870. (c) Nasir, M. S.; Cohen, B. I.; Karlin, K. D. *J. Am. Chem. Soc.* **1992**, *114*, 2482–2494. (d) Karlin, K. D.; Tyeklár, Z.; Farooq, A.; Haka, M. S.; Ghosh, P.; Cruse, R. W.; Gultneh, Y.; Hayes, J. C.; Zubieta, J. *Inorg. Chem.* **1992**, *31*, 1436–1451.

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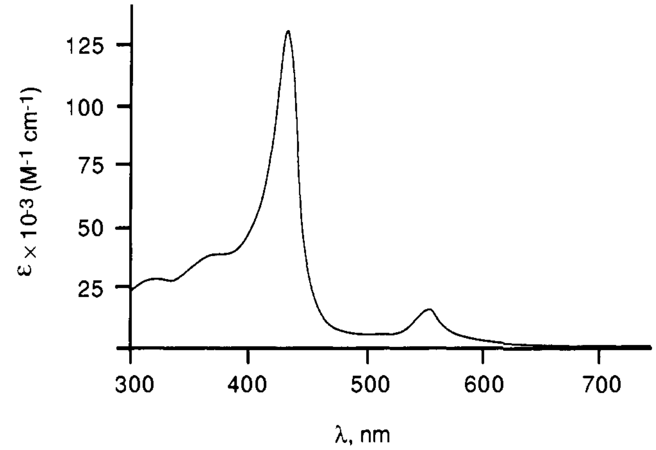
(7) (a) A recent report indicates a four N-ligand coordination for Cu$_B$ in cytochrome *ba*$_3$ from *Thermus thermophilus*: Surerus, K. K.; Oertling, W. A.; Fan, C.; Gurbiel, R. J.; Einarsdóttir, O.; Antholine, W. E.; Dyer, R. B.; Hoffman, B. M.; Woodruff, W. H.; Fee, J. A. *Proc. Natl. Acad. Sci. U.S.A.* **1992**, *89*, 3195–3199. (b) Other studies on bacterial oxidases implicate *three* His ligands for Cu$_B$: Minagawa, J.; Mogi, T.; Gennis, R. B.; Anraku, Y. *J. Biol. Chem.* **1992**, *267*, 2096–2104, and Shapleigh, J. P.; Hosler, J. P.; Tecklenburg, M. M. J.; Kim, Y.; Babcock, G. T.; Gennis, R. B.; Ferguson-Miller, S. *Proc. Natl. Acad. Sci., U.S.A.* **1992**, *89*, 4786–4790.

(8) (a) [(F$_8$-TPP)Fe-(O_2^{2-})-Cu(TMPA)](ClO_4) (**3**-(ClO_4)): Anal. Calcd for $C_{62}H_{38}ClCuF_8FeN_8O_6$: C, 57.40; H, 2.93; N, 8.64. Found: C, 57.30; H, 3.06; N, 8.48. IR (Nujol): $\nu(ClO_4) = 1090$ cm^{-1} (s, br). (b) [(F$_8$-TPP)-Fe-(O_2^{2-})-Cu(TMPA)](PF_6) (**3**-(PF_6)): Anal. Calcd for $C_{62}H_{38}CuF_{14}FeN_8O_2P$: C, 55.38; H, 2.82; Cu, 4.72; F, 19.80; N, 8.33. Found: C, 55.09; H, 2.80; Cu, 5.42; F, 19.36; N, 8.38. IR (Nujol): $\nu(PF_6) = 840$ cm^{-1} (s, br).

(9) For the complex presumed to be [(TPP)Fe-(O_2^{2-})-Cu(TMPA)](ClO_4), $\lambda_{max} = 439$ (Soret), 558 and 598 (α,β bands) in CH_3CN or CH_2Cl_2 solvent.

(10) (a) Kent, T. A.; Young, L. J.; Palmer, G.; Fee, J. A.; Münck, E. *J. Biol. Chem.* **1983**, *258*, 8543–8546. (b) Kent, T. A.; Münck, E.; Dunham, W. R.; Filter, W. F.; Findling, K. L.; Yoshida, T.; Fee, J. A. *J. Biol. Chem.* **1982**, *257*, 12489–12492. (c) Rusnak, F. M.; Münck, E.; Nitsche, C. I.; Zimmerman, B. H.; Fee, J. A. *J. Biol. Chem.* **1987**, *262*, 16328–16332.

most high-spin (TPP)Fe^{III} complexes. However, this compares well with that seen for the high-spin peroxo Fe(III) complex (with side-on η^2:η^2 coordination), [(TPP)Fe(O_2^{2-})]$^-$, characterized by Valentine and co-workers;[11] the red shift of the Soret band has been attributed to the dinegative charge of the peroxo ligand.[11b]



(2) Complex **3** is EPR silent (77 K), consistent with the coupled integer-spin formulation. (3) In an infrared spectrum, **3** possesses a band at 855 cm^{-1} not seen in **1**, **2**, or other (F_8-TPP)Fe-X (X = Cl$^-$, OH$^-$) compounds. When **3** is prepared using $^{18}O_2$ (99%), the 855-cm^{-1} band largely disappears, and a greatly enhanced absorption is seen at ~780-790 cm^{-1}, where other bands already occur. Additional studies will be required to determine an assignment.[12] (4) The ^{1}H NMR spectrum of **3** (CD_3CN) indicates that only a single porphyrin species is present, exhibiting a pyrrole H-resonance at 65 ppm, split meta phenyl signals at 9.6 and 9.2 ppm, and a para phenyl absorption at 7.8 ppm. These observations are also consistent with a high-spin Fe(III) environment and are again comparable to [(TPP)Fe(O_2^{2-})]$^-$ (61, 9.2, and 7.2 ppm, respectively).[13] The pyrrole signal assignment in **3** was confirmed by ^{2}H NMR spectroscopy of the pyrrole deuteriated porphyrin. (5) The room temperature magnetic moment of **3** is 5.2 ± 0.2 μ_B (Evans method in CD_3CN), a value consistent with the suggestion that **3** is a coupled $S = {}^5/_2$ (i.e., heme) and $S = {}^1/_2$ (i.e., Cu(II)) system. Further temperature dependent magnetic studies are needed.

Additional chemical evidence for a peroxo group in [Fe^{III}-(O_2^{2-})-Cu^{II}](ClO_4) (**3**) comes from reactivity with CO_2 and SO_2 (Scheme I), reagents which are often used to react with metal-dioxygen complexes.[14-16] Carbon dioxide reacts with **3**, and a carbonato dinuclear complex [{(TMPA)Cu}$_2$(CO_3)]$^{2+}$[17] and (F_8-TPP)Fe-OH[18] were isolated after workup. Since [(TPP)-Fe-(O_2^{2-})]$^-$ is known to react with SO_2 to give sulfate,[16] a better test is the reaction of SO_2 with **3**. Here, exposure to SO_2, decomposition with HCl(aq), and addition of Ba^{2+} demonstrate that sulfate is indeed produced. The isolated gravimetrically determined yield is 50%; when the TPP analogue [(TPP)Fe-(O_2^{2-})-Cu(TMPA)]$^+$[9] is tested in this manner, a 70% yield can be obtained. Neither (F_8-TPP)Fe-OH nor [(TMPA)Cu(Cl)]$^+$ gives sulfate upon reaction with SO_2.

In conclusion, the reaction of O_2 with porphyrin-Fe(II) and Cu(I) complexes leads to dinuclear peroxo-bridged [Fe^{III}-(O_2^{2-})-Cu^{II}]$^+$ (**3**) species. A complete electronic/magnetic and structural description of **3** is underway. Spectroscopically detected intermediates involving heme a_3 and O_2 or reduced derivatives (e.g., peroxo or ferryl) have been implicated in C*c*O action;[1] bridged Fe/Cu[1a,b,19] or discrete copper-dioxygen species[20] also may be involved. The results described here represent a conspicuous step toward developing systems which may aid in understanding O_2-reduction mechanism(s), structures, and protonation steps involving both (porphyrin)iron and copper ion.

Acknowledgment. We are grateful for the support of the National Institutes of Health (GM 28962, K.D.K.) and National Science Foundation (NSF DMB9001530, B.H.H.).

Registry No. 1, 141981-26-2; **2**, 114581-82-7; **3**-(ClO_4), 141981-28-4; **3**-(PF_6), 141981-31-9; C *c* O, 9001-16-5; (TPP)Fe-pip$_2$, 17845-65-7; [(TPP)Fe-(O_2^{2-})Cu(TMPA)](ClO_4), 141981-30-8; [{(TMPA)-Cu}$_2$$CO_3$]$^{2+}$, 118458-34-7; SO_2, 7446-09-5; CO_2, 124-38-9; $BaSO_4$, 7727-43-7; O_2^{2-}, 14915-07-2.

Supplementary Material Available: Mössbauer spectra of **3**-ClO_4 (1 page). Ordering information is given on any current masthead page.

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[11] (a) McCandlish, E.; Miksztal, A. R.; Nappa, M.; Sprenger, A. Q.; Valentine, J. S.; Stong, J. D.; Spiro, T. G. *J. Am. Chem. Soc.* **1980**, *102*, 4268-4271. (b) Burstyn, J. N.; Roe, J. A.; Miksztal, A. R.; Shaefitz, B. A.; Lang, G.; Valentine, J. S. *J. Am. Chem. Soc.* **1988**, *110*, 1382-1388.

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Asymmetric Desymmetrization by Enantioselective Catalysis of Carbonyl-Ene Reaction: Remote Internal Asymmetric Induction

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"Asymmetric desymmetrization"[1] of a symmetrical and achiral molecule is a basic and potential methodology for asymmetric synthesis. While the ability of enzymes to transform differentially symmetrical, hence enantiotopic, functional groups is well known,[2] little exploration has been performed on a similar ability of nonenzymatic catalysts,[3] particularly for C-C bond formation.[4] Recently, we developed an asymmetric catalytic carbonyl-ene reaction with prochiral glyoxylate as an efficient method for asymmetric C-C bond formation.[5] The asymmetric catalytic reaction involving a prochiral ene component with planar sym-

Table I. Asymmetric Desymmetrization of **2**.

entry	molarity (**2** : **3**)	% yield^a	*syn* (% ee) : *anti*
1	1.0 : 1.0	62 (27)	>99 (>99) : <1
2	1.0 : 2.0	57 (27)	>99 (>99) : <1

^{a} Calculated value based on the recovery of **2**. Value in parenthesis refers to the isolated yield.

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