d) J. L. Sessler, A. Andrievsky, P. A. Gale, V. Lynch, *Angew. Chem.* **1996**, *108*, 2954 – 2957; *Angew. Chem. Int. Ed. Engl.* **1996**, *35*, 2782 – 2785; e) B. F. Abrahams, B. F. Hoskins, D. M. Michail, R. Robson, *Nature* **1994**, *369*, 727 – 729.

[2] a) G. R. Desiraju, *Acc. Chem. Res.* **1996**, *29*, 441 – 449; b) O. M. Yaghi, H. Li, T. L. Groy, *J. Am. Chem. Soc.* **1996**, *118*, 9096 – 9101; c) P. Bhyrappa, S. R. Wilson, K. S. Suslick, *J. Am. Chem. Soc.* **1997**, *119*, 8492 – 8502.

[3] a) M. Iwaoka, S. Tomoda, *J. Am. Chem. Soc.* **1994**, *116*, 4463 – 4464; b) J. J. Novoa, M. C. Rovira, C. Rovira, J. Veciana, J. Tarres, *Adv. Mater.* **1995**, *7*, 233. c) V. R. Pedireddi, S. Chatterjee, A. Ranganathan, C. N. R. Rao, *J. Am. Chem. Soc.* **1997**, *119*, 10867 – 10868.

[4] a) A. Jasat, D. Dolphin, *Chem. Rev.* **1997**, *97*, 2267 – 2340, and references therein; b)J. L. Sessler, M. C. Hoehner, A. Gebauer, A. Andrievsky, V. Lynch, *J. Org. Chem.* **1997**, *62*, 9251 – 9260.

[5] R. Paolesse, S. Licoccia, M. Spagnoli, T. Boschi, R. G. Khoury, K. M. Smith, *J. Org. Chem.* **1997**, *62*, 5133 – 5137.

[6] P. J. Chmielewski, L. Latos-Grażyński, K. Rachlewicz, *Chem. Eur. J.* **1995**, *1*, 68 – 73.

[7] H. A. Potts, G. F. Smith, *J. Chem. Soc.* **1957**, 4018 – 4020.

[8] Such an intermediate (sapphyrinogen) has been proposed by Latos-Grażyński for the formation of sapphyrins; see reference [6]. Experiments are in progress to monitor the formation of rubyrinogen by UV absorption spectroscopy.

[9] We would like to thank the referee who brought to our attention a recent paper by Latos-Grażyński and co-workers published after submission of this manuscript in which an asymmetric tautomer for 5,10,15,20-tetraphenyl-26,28-dithiasapphyrin was proposed. For details see: K. Rachlewicz, N. Sprutta, P. J. Chmielewski, L. Latos-Grażyński, *J. Chem. Soc. Perkin Trans. 2* **1998**, 969 – 975.

[10] a) Crystal structure data of **5**: $C_{48}H_{32}N_3S_2 \cdot CH_2Cl_2$, $M_r = 799.87$; crystals from CH_2Cl_2/CH_3OH (1/1); Crystal dimensions $0.50 \times 0.25 \times 0.20$ mm; triclinic, space group $P\bar{1}$, $a = 11.122$ (2), $b = 13.526$ (2), c = 15.109 (2) Å, $\alpha = 68.689$ (13), $\beta = 87.10$ (2), $\gamma = 66.785$ (11)°, $V = 1934.6$ (6) Å^3, $Z = 2$, $\rho_{calcd} = 1.373$ g cm^{-3}; F (000) = 830; μ ($Mo_{K\alpha}$) = 3.2 cm^{-1}; 12202 measured reflections; 5833 observed reflections. ($F_o^2 > 2\sigma F_o^2$); $\theta_{max} = 28.3°$; $R = 0.0681$, $R_w = 0.1658$. b) The X-ray diffraction data were collected on a Siemens SMART3-circle diffractometer equipped with a CCD detector. The structure was solved by the direct method using the SHELX-904 program and refined by the least squares method on F^2 using SHELXTL Version 5.03.5. Crystallographic data (excluding structure factors) for the structures reported in this paper have been deposited with the Cambridge Crystallographic Data Center as supplementary publication no. CCDC-101360. Copies of the data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK (fax: (+44) 1223-336-033; e-mail: deposit@ccdc.cam.ac.uk).

[11] Crystal structure data of **6**: $C_{48}H_{32}N_3Se_2 \cdot CH_2Cl_2$, $M_r = 891.60$; crystals from CH_2Cl_2/CH_3OH (1/1); crystal dimensions $0.10 \times 0.20 \times 0.35$ mm; triclinic, space group $P\bar{1}$, $a = 11.2565$ (14), $b = 13.689$ (2), $c = 15.116$ (2) Å, $\alpha = 67.911$ (7), $\beta = 86.897$ (9), $\gamma = 66.592$ (2)°, $V = 1968.1$ (5) Å^3, $Z = 2$, $\rho_{calcd} = 1.505$ g cm^{-3}; F (000) = 898; 11111 measure reflections; 7648 observed reflections. ($F_o^2 > 2\sigma F_o^2$); $\theta_{max} = 26.41°$; $R = 0.0510$, $R_w = 0.1099$.[10b]

[12] J. Lisowski, J. L. Sessler, V. Lynch, *Inorg. Chem.* **1995**, *34*, 3567 – 3572.

[13] E. Vogel, M. Kocher, H. Schmickler, J. Lex, *Angew. Chem.* **1986**, *98*, 262; *Angew. Chem. Int. Ed. Engl.* **1986**, *25*, 257 – 259.

[14] The ^{1}H NMR spectra of **6** which was recrystallized from dichloromethane and *n*-heptane showed sharp resonances (12.15 Hz), whereas the resonances were broad (20.1 Hz) for the sample recrystallized from a dichloromethane/methanol mixture. Furthermore, a titration of different concentrations of CD_3OD to a $CDCl_3$ solution of **6** resulted in gradual broadening of the signals, suggesting the existence of aggregates due to intermolecular interactions in solution.

[15] A. Srinivasan, M. V. Reddy, S. J. Narayanan, B. Sridevi, S. K. Pushpan, M. Ravikumar, T. K. Chandrashekar, *Angew. Chem.* **1997**, *109*, 2710 – 2713; *Angew. Chem. Int. Ed. Engl.* **1997**, *36*, 2598 – 2601.

A Functional Model of Cytochrome c Oxidase: Thermodynamic Implications**

James P. Collman,* Lei Fu, Paul C. Herrmann, Zhong Wang, Miroslav Rapta, Martin Bröring, Reinhold Schwenninger, and Bernard Boitrel

Cytochrome c oxidases (CcOs) are the terminal enzymes of the respiratory chains. These membrane bound assemblies catalyze the four-electron ($4\,e^-$), four-proton ($4\,H^+$) reduction of O_2 to H_2O, and couple this exergonic reaction to intramembrane proton translocation. The resulting energy is used to generate ATP as protons flow back through the membrane via ATP synthase.[1, 2] What makes this class of enzymes particularly well suited to the task is the fact that they do not release partially reduced intermediates, such as superoxide and peroxide, which would be devastating to the cell if released in large quantities.[3]

Recently, a plethora of research on CcO[4] has been stimulated by two X-ray crystal structures.[5–8] The fundamental question of how the enzymes convert O_2 into H_2O without releasing H_2O_2 remains unanswered, however. Attempts to prepare synthetic analogues of the O_2 binding/activating site in CcO have been reported over many years. Very few have mimicked the catalytic properties of CcO, however.[9]

Previously we reported the first functional CcO model that consisted of a Co^{II} – porphyrin with a Cu^{I}-coordinated distal superstructure and with a covalently attached imidazole group as the axial ligand.[10] We demonstrated that this complex catalyzes the $4\,e^-$ reduction of O_2 under physiological conditions without the release of H_2O_2. Our electrocatalytic studies also demonstrate that both the copper ion and the axial imidazole ligand are essential to achieve the reduction.

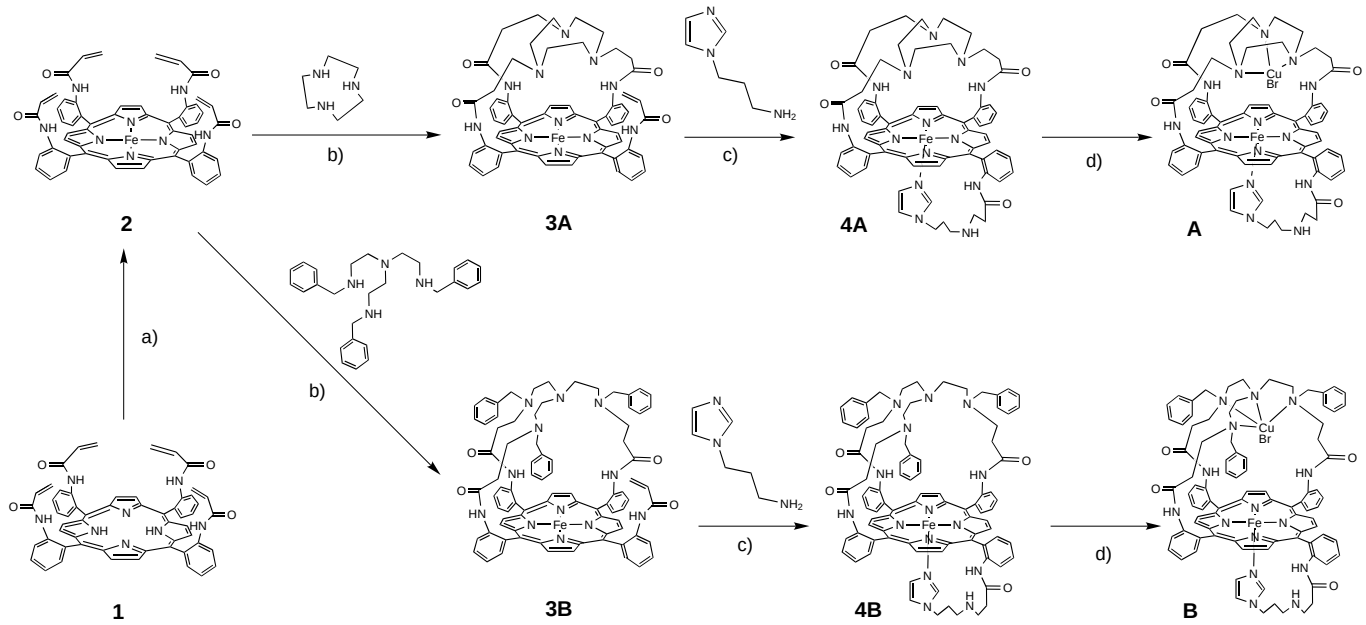
Herein we present the synthesis, characterization, and electrocatalytic chemistry of two Fe/Cu-containing synthetic analogues of the dioxygen activating site of CcO heme a_3 Cu_B. The only structural difference between these compounds is the nature of the distal superstructure in which the copper ion resides (Scheme 1). Compound **A** has a 1,4,7-triazacyclononane (TACN) distal cap whereas **B** features a *N*,*N*′,*N*″-tribenzyl-tris(aminoethyl)amine (TBTren) cap.

Compounds **A** and **B** both form stable 1:1 adducts with O_2 ($\mathbf{X_A}$ and $\mathbf{X_B}$, respectively) as demonstrated by UV/Vis spectroscopy after O_2-titration. The O_2 adduct of each compound features an apparently diamagnetic NMR spectrum[11] in contrast to the paramagnetic NMR spectrum observed with their O_2-free forms, **A** and **B**. This observation

[*] Prof. Dr. J. P. Collman, Dr. L. Fu, Dr. P. C. Herrmann, Dr. Z. Wang, Dr. M. Rapta, Dr. M. Bröring, Dr. R. Schwenninger, Dr. B. Boitrel
Department of Chemistry
Stanford University
Stanford, CA 94305 – 5080 (USA)
Fax: (+1) 650-725-0259
E-mail: jpc@chem.stanford.edu

[**] We thank the NIH (grant 1R01 GM-17880-28) and the NSF (grant CHE 9612725) for financial support. We also thank Drs. Henry Taube, Jean-Claude Marchon, and Steve Harford for helpful discussions.

Supporting information for this article is available on the WWW under http://www.wiley-vch.de/home/angewandte/ or from the author.



Scheme 1. Synthesis of the CcO model compounds **A** and **B**. a) $FeBr_2$, THF, △; b) methanol, △; c) methanol/toluene (1/5), △; d) CuBr, CH_3CN, △.

is consistent with the Fe^{III} and Cu^{II} centers being strongly antiferromagnetically coupled through a bridging peroxide group.

In both cases cobaltocene (Cp_2Co) can reduce the O_2 adduct to its deoxygenated form. Whereas complex $\mathbf{X_A}$ requires only two equivalents of Cp_2Co to regenerate **A**, $\mathbf{X_B}$ requires four equivalents to form the deoxygenated complex **B**. Both **A** and **B** were applied to a rotating ring-disk electrode (RRDE).[12] Compound **A** produced H_2O_2 from reduction of O_2 at pH 7, while **B** did not (Figure 1). Consequently we conclude that compound **A** predominately catalyzes the $2e^-$ reduction of O_2 to H_2O_2, while **B** catalyzes the $4e^-$ reduction of O_2 to H_2O under physiological conditions.

The different half-wave potentials measured by cyclic voltammetry demonstrate the effect of the distal superstructure on the Cu^I/Cu^{II} potential.[9] For the two different distal caps studied, not only are the absolute Cu^I/Cu^{II} potentials at different values, but the relation of the Fe – Cu potentials to each other differs as well. The TACN cap, which presents the copper ion with three nitrogen atoms, makes the Cu^{II} oxidation state less favorable than that of the TBTren cap that contains four nitrogen atoms. In the latter complex, the iron center should be reduced first, which possibly directs the binding of O_2 to the distal porphyrin locus.

To comprehend the thermodynamics of the $4e^-$ reduction, the electrochemical potential of the reaction is converted into ΔG.[13] The $4e^-$ reduction of O_2 catalyzed by the model catalyst (cat.) on the graphite disk can be written by Equations (1) to (3).

$$\text{cat.} + O_2 \rightleftharpoons \text{cat.}\cdot O_2^{2-} \qquad \Delta G_1^{\mathrm{B}} \qquad (1)$$

$$\text{cat.}\cdot O_2^{2-} + 4e^- + 4H^+ \rightleftharpoons 2H_2O + \text{cat.} \qquad \Delta G_2^{\mathrm{B}} \qquad (2)$$

$$O_2 + 4e^- + 4H^+ \rightleftharpoons 2H_2O \qquad \Delta G_{\mathrm{overall}}^{\mathrm{B}} \qquad (3)$$

Since step 1 [Eq. (1)] occurs spontaneously in solution only the second step [Eq. (2)] should require the input of electrons from the graphite disk. The potential recorded during the RRDE experiments (see Figure 1) represents the value of the second step (ΔG_2^{B}) alone. Thus, by subtracting this value from the overall reduction of O_2 ($\Delta G_{\mathrm{overall}}^{\mathrm{B}}$)[14] the lower limit of ΔG_1^{B} may be estimated. The calculated values are shown in Table 1 and illustrated graphically in Scheme 2.

It is significant that compound **B**, which catalyzes the $4e^-$ reduction of O_2 to H_2O, releases at least 47.4 kcal mol^{-1} of energy upon the addition of O_2 in the absence of a reducing agent (Table 1). The formation of this very stable intermediate ($\mathbf{X_B}$) results in the conversion of $\mathbf{X_B}$ into H_2O_2 being endergonic and thermodynamically unfavorable.[15] Therefore, the conversion of $\mathbf{X_B}$ into H_2O becomes a predominant pathway if it is kinetically possible (Scheme 2B).

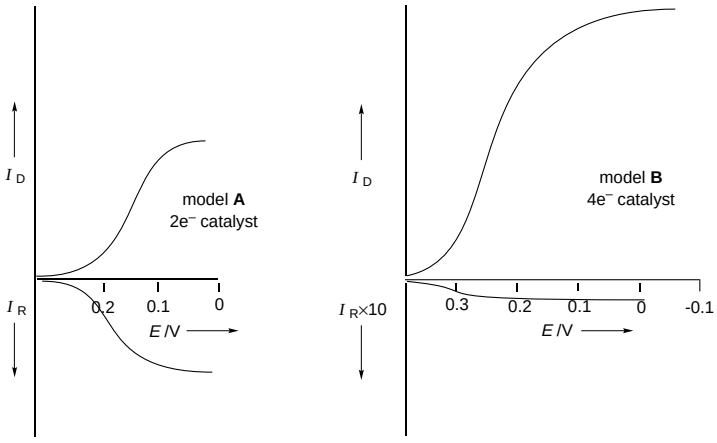


Figure 1. The RRDE experiment profiles (0.025 M phosphate buffer, pH 7; disk area 0.46 cm^2; scan rate 100 mV s^{-1}; collection efficiency 0.15; ring potential +1.1 V versus normal hydrogen electrode (NHE)). I_D = disk current; I_R = ring current.

  1433-7851/98/3724-3398 $ 17.50+.50/0

Table 1. Thermodynamic data for the reduction of dioxygen.

Reaction	E [V] vs NHE (at pH 7)	ΔG [kcal mol^{-1}] ($= -nFE$)
$O_2 + 2e^- + 2H^+ \rightleftharpoons H_2O_2$ ($[H_2O_2] = 1$ M)	0.282[a]	−13.0
$O_2 + 2e^- + 2H^+ \rightleftharpoons H_2O_2$ ($[H_2O_2] = 10^{-6}$ M)		−16.6
$O_2 + 4e^- + 4H^+ \rightleftharpoons 2H_2O$	0.816[a]	−75.1
for model catalyst ***A***	0.20[b]	−9.2
$\mathbf{A}\cdot O_2 + 2e^- + 2H^+ \rightleftharpoons H_2O_2 + \mathbf{A}$		
$O_2 + \mathbf{A} \rightleftharpoons \mathbf{A}\cdot O_2$		−7.4[c]
for model catalyst ***B***	0.30[b]	−27.6
$\mathbf{B}\cdot O_2 + 4e^- + 4H^+ \rightleftharpoons 2H_2O + \mathbf{B}$		
$O_2 + \mathbf{B} \rightleftharpoons \mathbf{B}\cdot O_2$		−47.4
for cytochrome c oxidase		
$\mathbf{CcO}\cdot O_2 + 4e^- + 4H^+ \rightleftharpoons 2H_2O + \mathbf{CcO}$	0.245	−22.6
$\mathbf{CcO} + O_2 \rightleftharpoons \mathbf{CcO}\cdot O_2$		−52.5

[a] Taken from reference [32]. [b] Taken from the RRDE experiments (see Figure 1). [c] Based on the assumption that $[H_2O_2] = 10^{-6}$ M.

In contrast, compound **A**, which catalyzes the $2e^-$ reduction of O_2 to H_2O_2 at lower potential, releases far less energy upon binding O_2 under the same conditions. The paths from $\mathbf{X_A}$ to H_2O_2 and H_2O are both exergonic. Therefore, the catalytic stability of **A** to form H_2O_2 or H_2O probably depends on the rate of hydrolysis of the peroxide intermediate (Scheme 2C).

Our model can also be compared to the CcO enzyme family by making the assumption that cytochrome c behaves similarly to the graphite electrode. The published value of its redox potential (0.245 V)[4] permits the calculation of ΔG for the O_2-binding step of CcO under standard conditions. This analysis yields a value of -52 kcal mol^{-1}, which is comparable to that obtained for **B**.

In conclusion, we have demonstrated that the state of the bound peroxide is very sensitive to the nature of the distal superstructure. Ultimately, the copper ion can determine the fate of the catalyzed reaction, and it appears to be the deciding factor as to whether the reaction yields a $2e^-$ or $4e^-$ product. We propose that in the reactions catalyzed by compound **B** and the enzyme family CcO the initial reaction of the fully reduced catalyst with O_2 to yield the peroxide intermediate is exergonic enough that it thermodynamically traps the bound peroxide. This effectively blocks the release of the poisonous H_2O_2 since its production would be endergonic. Hence the CcO-catalyzed reaction can be limited by proton transfer even though there is a build up of peroxide intermediates. Since these intermediates are low enough in energy, relative to any toxic products, there is very little risk of dangerous compounds being released even though the concentration of the peroxide intermediate may be high.

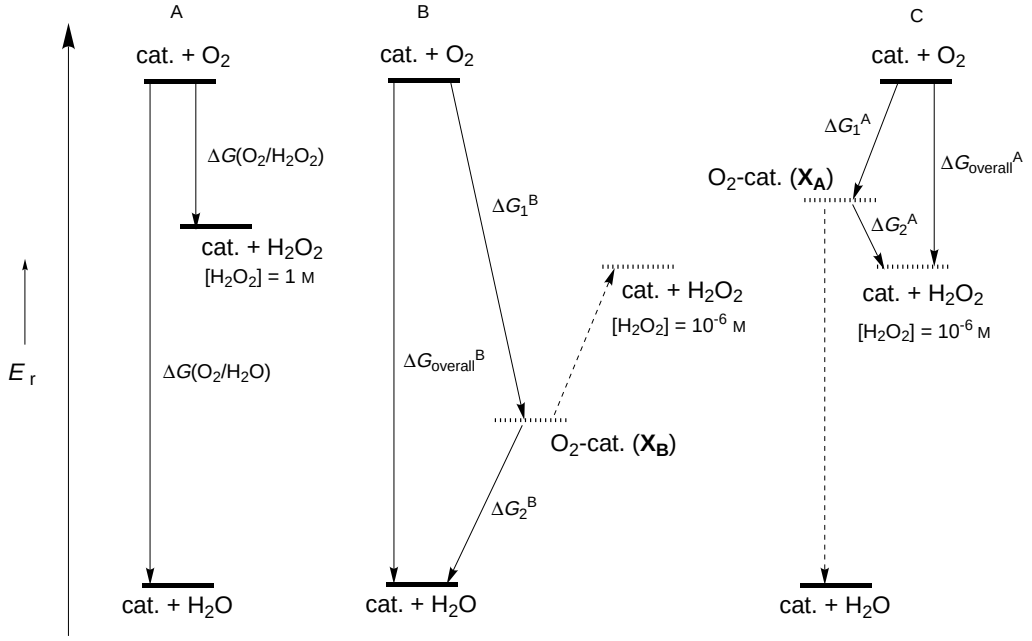
Experimental Section

The Michael acceptor **1** was metallated with $FeBr_2$ to yield **2**.[16] Compound **A** was prepared by capping **2** with 1,4,7-triazacyclononane (TACN), attaching a substituted imidazole tail in refluxing methanol/toluene, purifying, and metallating with CuBr in refluxing acetonitrile according to the reported method.[10, 17] The synthesis of compound **B** followed the same protocol except the metallated Michael acceptor **2** was capped with TBTren instead of TACN. All new compounds were fully characterized by spectroscopic methods (see the supporting information).

Received: June 16, 1998 [Z11998IE]
German version: *Angew. Chem.* **1998**, *110*, 3592 – 3595

Keywords: cytochrome c oxidase · electrochemistry · heme proteins · N ligands · O – O activation

[1] L. Stryer, *Biochemistry*, 4th ed, Freeman, New York, **1995**.
[2] M. Wikström, *Nature* **1977**, *266*, 271 – 273.
[3] M. A. J. Rodgers, E. L. Powers, *Oxygen and Oxy-Radicals in Chemistry and Biology,* Academic Press, New York, **1981**.
[4] S. Ferguson-Miller, G. T. Babcock, *Chem. Rev.* **1996**, *96*, 2889 – 2907.
[5] S. Iwata, C. Ostermeier, B. Ludwig, H. Michel, *Nature* **1995**, *376*, 660 – 669.
[6] T. Tsukihara, H. Aoyama, E. Yamashita, T. Tomizaki, H. Yamaguchi, K. Sinzawa-Itoh, R. Nakashima, R. Yaono, S. Yoshikawa, *Science* **1995**, *269*, 1069 – 1074.



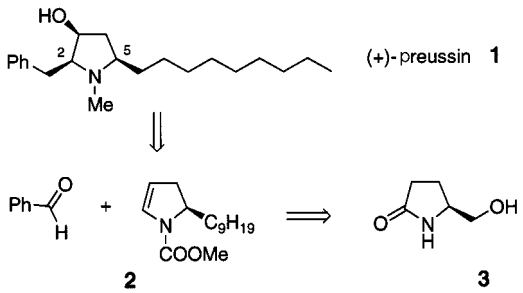
Scheme 2. Proposed energy diagram of dioxygen reduction. A) Thermodynamic data; B) the $4e^-$ reduction of O_2; C) the $2e^-$ reduction of O_2. E_r = relative energy.

[7] T. Tsukihara, H. Aoyama, E. Yamashita, T. Tomizaki, H. Yamaguchi, K. Shinzawa-Itoh, R. Nakashima, R. Yaono, S. Yoshikawa, *Science* **1996**, *272*, 1136 – 1144.
[8] S. Yoshikawa, K. Shinzawaitoh, R. Nakashima, R. Yaono, E. Yamashita, N. Inoue, M. Yao, M. J. Fei, C. P. Libeu, T. Mizushima, H. Yamaguchi, T. Tomizaki, T. Tsukihara, *Science* **1998**, *280*, 1723 – 1729.
[9] J. P. Collman, *Inorg. Chem.* **1997**, *36*, 5145 – 5155.
[10] J. P. Collman, L. Fu, P. C. Herrmann, X. Zhang, *Science* **1997**, *275*, 949 – 951.
[11] A more detailed discussion can be found in references [18 – 25].
[12] The RRDE consists of a graphite disk concentrically placed inside a platinum ring.[26, 27] During our experiment the assembly was submerged in an O_2-saturated, buffered (pH 7) solution, rotated at a constant rate, and then voltage was applied. The current produced at the platinum ring is correlated to the concentration of H_2O_2 produced.[28–31]
[13] The potential is converted into ΔG with the equation $\Delta G = -nFE$, where n is the number of electrons per mole, F is Faraday's constant, and E is the experimental reduction potential for the stated reaction.
[14] In the case of compound **B** the value of $\Delta G^{B}_{overall}$ can be compared to the standard ΔG value for the conversion of O_2 into H_2O since the concentrations of all pertinent species are known.
[15] The ΔG value for the O_2/H_2O_2 couple will be more negative if the activity of H_2O_2 is below 1.0 M in our experimental conditions.
[16] J. P. Collman, X. Zhang, P. C. Herrman, E. S. Uffelman, B. Boitrel, A. Straumanis, J. I. Brauman, *J. Am. Chem. Soc.* **1994**, *116*, 2681 – 2682.
[17] J. P. Collman, B. Boitrel, L. Fu, J. Galanter, A. Straumanis, M. Rapta, *J. Org. Chem.* **1997**, *2*, 193 – 194.
[18] G. N. La Mar, G. R. Eaton, R. H. Holm, F. A. Walker, *J. Am. Chem. Soc.* **1973**, *95*, 63 – 75.
[19] G. N. La Mar, F. A. Walker, *J. Am. Chem. Soc.* **1973**, *95*, 1782 – 1790.
[20] H. Goff, G. N. La Mar, C. A. Reed, *J. Am. Chem. Soc.* **1977**, *99*, 3641 – 3644.
[21] H. Goff, G. N. La Mar, *J. Am. Chem. Soc.* **1977**, *99*, 6599 – 6606.
[22] J. P. Collman, J. I. Brauman, K. M. Doxsee, T. R. Halbert, E. Bunnenberg, R. E. Linder, G. N. La Mar, J. Del Gaudio, G. Lang, K. Spartalian, *J. Am. Chem. Soc.* **1980**, *102*, 4182 – 4192.
[23] J. P. Collman, J. I. Brauman, T. J. Collins, B. L. Iverson, G. Lang, R. G. Pettman, J. L. Sessler, M. A. Walters, *J. Am. Chem. Soc.* **1983**, *105*, 3038 – 3052.
[24] J. P. Collman, P. C. Herrmann, B. Boitrel, X. Zhang, T. A. Eberspacher, L. Fu, *J. Am. Chem. Soc.* **1994**, *116*, 9783 – 9785.
[25] J. P. Collman, P. C. Herrmann, L. Fu, T. A. Eberspacher, M. Eubanks, B. Boitrel, P. Hayoz, X. Zhang, J. I. Brauman, *J. Am. Chem. Soc.* **1997**, *119*, 3481 – 3489.
[26] W. J. Albery, M. L. Hitchman, *Ring-Disc Electrodes,* Clarendon Press, Oxford, **1971**.
[27] T. Geiger, F. C. Anson, *J. Am. Chem. Soc.* **1981**, *103*, 7489 – 7496.
[28] V. G. Levich, *Physiochemical Hydrodynamics*, Prentice-Hall, Englewood Cliffs, NJ, **1962**.
[29] A. J. Bard, L. R. Faulkner, *Electrochemical Methods: Fundamentals and Applications*, Wiley, New York, **1980**.
[30] J. Koutecky, V. G. Levich, *Zh. Fiz. Khim.* **1956**, *32*, 1565 – 1575.
[31] J. P. Collman, P. S. Wagenknecht, J. Hutchison, *Angew. Chem.* **1994**, *106*, 1620 – 1639. *Angew. Chem. Int. Ed. Engl.* **1994**, *33*, 1537 – 1554.
[32] *Standard Potentials in Aqueous Solution* (Eds.: A. J. Bard, R. Parsons, J. Jordon), Marcel Dekker, New York, **1985**.

Unprecedented Facial Diastereoselectivity in the Paternò – Büchi Reaction of a Chiral Dihydropyrrole—A Short Total Synthesis of (+)-Preussin**

Thorsten Bach* and Harm Brummerhop

The Paternò – Büchi reaction[1] of aromatic aldehydes with enol and enamine derivatives gives 3-heteroatom-substituted 2-aryloxetanes in good yield.[2] Subsequent Pd-catalyzed hydrogenolysis of these compounds leads to a bond cleavage between the oxygen atom and the C2 atom of the oxetane and yields the products of a formal carbohydroxylation.[3] The carbohydroxylation of the N-acceptor-substituted 2,3-dihydropyrrole **2** appealed to us as an approach to the antifungal pyrrolidinol alkaloid (+)-preussin[4] (**1**). A straightforward synthesis[5] of this natural product appeared possible from the commercially available (*S*)-pyroglutaminol (**3**; Scheme 1).



Scheme 1. Retrosynthesis of (+)-preussin (**1**).

We now report on the realization of this goal in which the pivotal Paternò – Büchi reaction of **2** proceeded with a substrate-induced facial diastereoselectivity previously unobserved in photocycloaddition reactions. Indeed, a bulky substituent within a five-membered ring is known to direct the attack of a reactant to the opposite face (*anti* attack). Examples of this are found in Paternò – Büchi reactions[6] and in intermolecular [2+2] photocycloadditions.[7] The thermal addition of ketenes to dihydropyrroles, which are analogues of **2**, also proceeded with *anti* attack to the existent substituent.[8] The notion that made us hope for the *syn* attack shown in Scheme 1 was based on an observation by Beckwith and Chai[9] in which they showed that in radical reactions of N-acceptor-substituted five-membered rings that bear a stereogenic center in the C2 position the radical center in the C5 position is attacked from the same face as the large substituent at C2 points to. Since Paternò – Büchi reactions are known to occur via radical intermediates[1, 10] a selection at

[*] Prof. Dr. T. Bach, Dipl.-Chem. H. Brummerhop
Fachbereich Chemie der Philipps-Universität
Hans-Meerwein-Strasse, D-35032 Marburg (Germany)
Fax: (+49) 6421-288917
E-mail: bach@chemie.uni-marburg.de

[**] This project was supported by the Deutsche Forschungsgemeinschaft (Ba 1372-3/1 and -3/2) and by the Fonds der Chemischen Industrie. We thank Gregor Willanzheimer for skillful technical assistance. A gift of chemicals from Witco GmbH (Bergkamen) is gratefully acknowledged.

  1433-7851/98/3724-3400 $ 17.50+.50/0