

Symmetrical and Unsymmetrical Quadruply Aza Bridged Closely Interspaced Cofacial Bis(5,10,15,20-tetraphenylporphyrin)s. 3. Interplanar Distances, ^1H NMR Chemical Shifts, and the Catalysis of the Electrochemical Reduction of Oxygen

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Abstract: The gas-phase geometries of the aza bridged cofacial porphyrin dimers 1-7 were calculated by the CHARM_m molecular dynamics method. It was found that the global minimum conformations of porphyrins 1-5 have a D_4 symmetry and those of dimers 6 and 7 have a C_2 symmetry. Electrochemical (rotating ring-disk electrode) reduction of O_2 via cobalt complexes of 1-4 and 6 establish both pathways of $4e^-$ reduction (to form water) and $2e^-$ reduction (to furnish hydrogen peroxide). The geometry and the center-to-center distance (Ct-Ct) between the two porphyrin cores in the dimers are crucial factors for determining the electroreduction pathway. Biscobalt dimers with Ct-Ct distances of less than 5 Å catalyze the reduction of dioxygen mainly through the $4e^-$ pathway, whereas those with Ct-Ct distances > 5.35 Å do via the $2e^-$ path. In contrast to the observations of Collman and Chang, we find that the peak potentials for the $4e^-$ reduction of O_2 via biscobalt porphyrin dimers 1-4 and 6 are comparable to that of the $2e^-$ reduction by the monocobalt porphyrin 8. Therefore, the precise geometry of the biscobalt tetraphenylporphyrin dimer is the crucial factor that determines $2e^-$ vs $4e^-$ reduction of O_2 while the reduction potential is independent of the path. The biscobalt cofacial porphyrins 1 and 2 represent the first rigid metalloporphyrin dimer system to catalyze effectively the $4e^-$ reduction of O_2 to water. Further, a linear correlation has been found between the solution ^1H NMR chemical shifts of the pyrrolic N-H resonances ($\delta' \text{NH}$) and the number of electrons transferred (n) in the reduction of dioxygen catalyzed by biscobalt dimeric porphyrins.

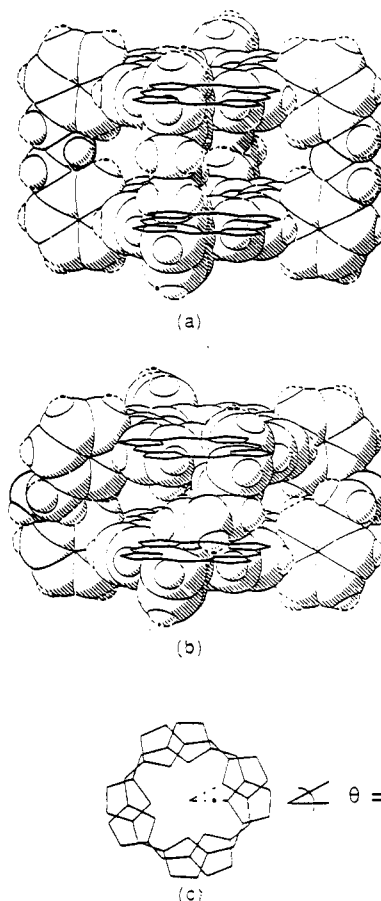
Introduction

A present goal in the mimicking of enzymatic catalysis is to position in purposeful proximity two porphyrin cores such that they may jointly enter into reactions.¹ The groups of Collman and Chang have prepared covalently linked porphyrin dimer systems in which the two metals in the centers of the porphyrin rings interact in a concerted fashion in the binding of O_2 and N_2 .¹ They were able to show that flexible dimers such as an anthracene pillar dicobalt porphyrin (having slipping flexibility) and dicobalt porphyrins linked by two amide chains between diametrical β -positions (Chart I) are capable of reducing dioxygen to water via the four-electron-reduction pathway without the intermediacy of hydrogen peroxide. On the other hand, they found that rigid systems with inappropriate center-to-center distances (Chart II) precluded any concerted coordination of the dioxygen molecule to the cobalt located in the centers of the porphyrin cores.²

Herein we report the first example of rigid water-soluble bisporphyrin structures (quadruply aza bridged closely interspaced cofacial biscobalt 5,10,15,20-tetraphenylporphyrins) which act as effective catalysts for the four-electron reduction of dioxygen to water.

Results and Discussion

Theoretical Calculations. The center-to-center distance is believed to be a determining factor for the efficiency of cofacial

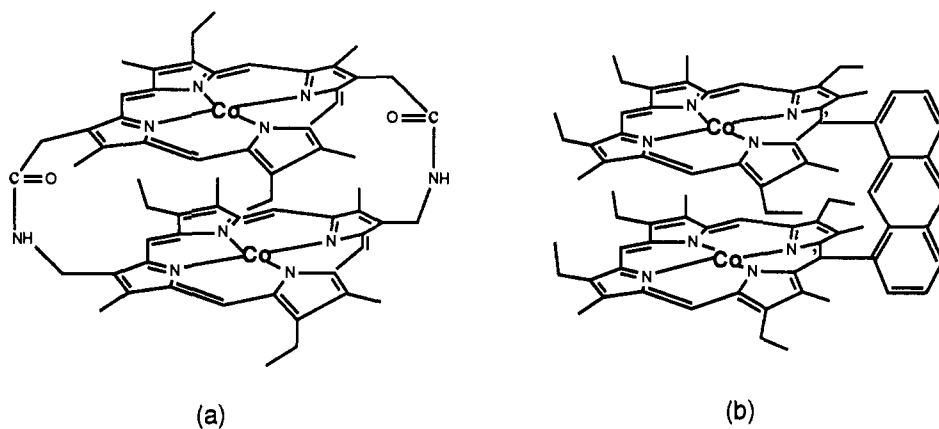


(1) (a) Collman, J. P.; Marrocco, M.; Denisevich, P.; Koval, C.; Anson, F. C. *J. Electroanal. Chem.* **1979**, *101*, 117. (b) Collman, J. P.; Denisevich, P.; Konai, Y.; Marrocco, M.; Koval, C.; Anson, F. C. *J. Am. Chem. Soc.* **1980**, *102*, 6027. (c) Geiger, T.; Anson, F. C. *J. Am. Chem. Soc.* **1981**, *103*, 7489. (d) Liu, H. Y.; Abdalmuhdi, I.; Chang, C. K.; Anson, F. C. *J. Phys. Chem.* **1985**, *89*, 665. (e) Liu, H. Y.; Weaver, M. J.; Wang, C.-B.; Chang, C. K. *J. Electroanal. Chem.* **1983**, *145*, 439. (f) Sawaguchi, T.; Matsue, T.; Itaya, K.; Uchida, I. *Electrochim. Acta* **1991**, *36*, 703. (g) Collman, J. P.; Hendricks, N. H.; Leidner, C. R.; Ngameni, E.; L'Her, M. *Inorg. Chem.* **1988**, *27*, 387. (h) Durand, R. R., Jr.; Bencosme, C. S.; Collman, J. P.; Anson, F. C. *Ibid.* **1983**, *105*, 2710. (i) Chang, C. K.; Liu, H. Y.; Abdalmuhdi, I. *J. Am. Chem. Soc.* **1984**, *106*, 2725. (j) Chang, C. K. *Adv. Chem. Ser.* **1979**, *173*, 162. (2) Collman, J. P.; Anson, F. C.; Bencosme, S.; Chong, A.; Collins, T.; Denisevich, P.; Evitt, E.; Geiger, T.; Ibers, J. A.; Jameson, G.; Konai, Y.; Koval, C.; Meier, K.; Okaley, P.; Pettman, R.; Schmittou, E.; Sessler, J. In *Organic Synthesis Today and Tomorrow*; Trost, B. M.; Hutchinson, C. R., Eds.; Pergamon Press: Oxford, 1981; pp 29-45.

Figure 1. (a) Shaded CPK model of the totally extended form of the porphyrin dimer. (b) Shaded CPK model of the totally screwed down form of the porphyrin dimer. (c) Distal view line drawing of the porphyrin rings of the totally screwed down form illustrating the angle $\theta = 26^\circ$.

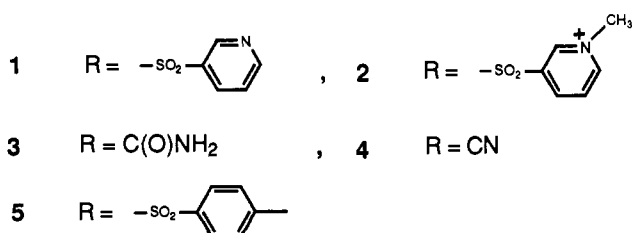
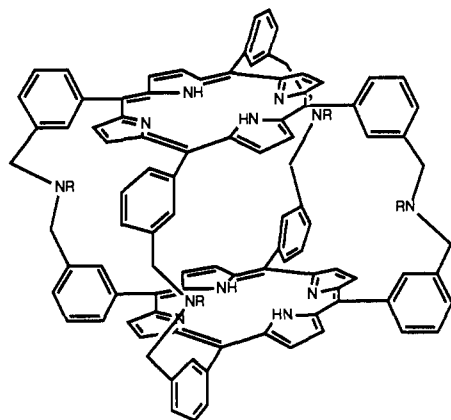
porphyrin dimers as electroreduction catalysts capable of catalyzing the $4e^-$ reduction of dioxygen to water.² Thus, knowledge

Chart I



^a (a) Doubly bridged dicobalt porphyrin linked via amide chains between diametrical β -positions. (b) An anthracene pillar dicobalt porphyrin.

of the geometrical structure of the dimeric porphyrin is imperative in predicting the efficacy of the catalyst. We have used the molecular mechanics empirical forcefield CHARM_m³ to calculate geometries for the dimeric porphyrins 1-7. The calculations were



initiated with "screwed-down" geometries (Figure 1), and extensive minimization was followed by CHARM_m molecular dynamics. The calculated global minima structures were analyzed in terms of the center-to-center distances (Ct-Ct), interplanar distances (P-P), and lateral shifts (LS) (see Figure 2 and Table I). Inspection of the optimum minimized dimer structures of 1-5 indicates that they have approximate D_4 symmetry, resulting from a screwing down action of one porphyrin core to approach the other (Figure 1). The dihedral angle $\theta_{N_1C_1C_2N_2}$ (see c of Figure 1) observed as a result of the screwed-down conformation is 26° . This angle coincides with the calculated optimal angle of closest cofacial proximity for two covalently unlinked tetraphenylporphyrin cores.⁴ Incidentally, the $\theta_{N_1C_1C_2N_2}$ angle reflects the extent to which the linker can be stretched or folded in the dimers. As the interplanar distance becomes smaller, due to the approach of the porphyrin rings, the total energy decreases until an energy minimum is

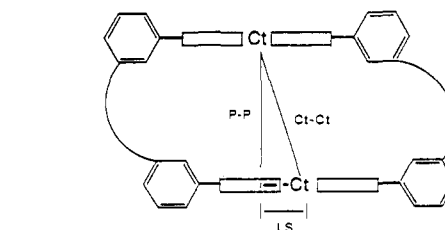


Figure 2. Schematic representation of the geometrical parameters used to describe the cofacial TPP dimers. Ct-Ct, center-to-center distance. P-P, interplanar separation. LS, lateral shift.

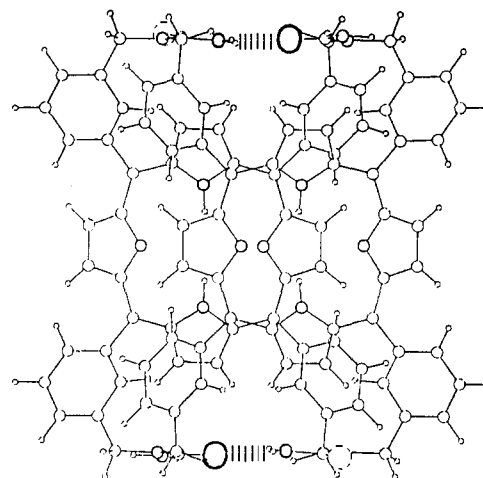
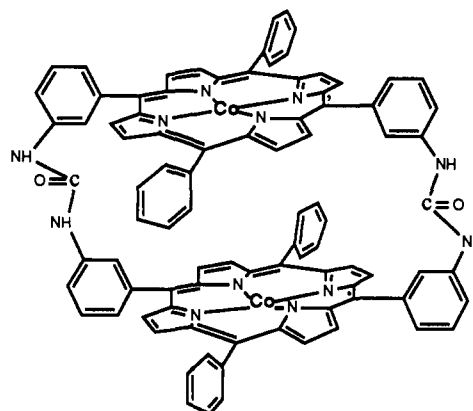


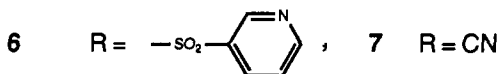
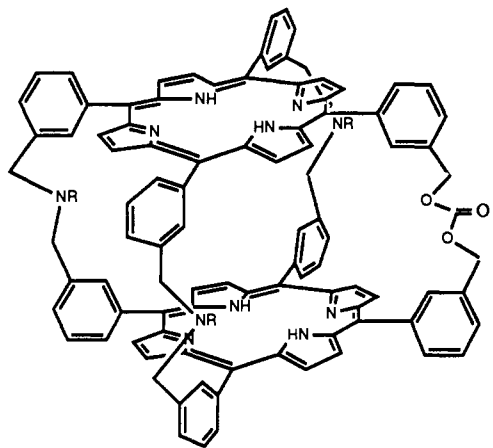
Figure 3. Top view of the CHARM_m-calculated global minimum structure for dimer 3. Considerable slipping of the porphyrin planes occurs as a result of intramolecular hydrogen bonds (dotted lines) between adjacent urea side chains.

Chart II. Diurea-Linked Binary Biscobalt Porphyrin



(3) Brooks, B. R.; Bruccoleri, R. E.; Olafson, B. D.; States, D. J.; Swaminathan, S.; Karplus, M. *J. Comput. Chem.* **1983**, *4*, 187.

(4) Karaman, R.; Almarsson, Ö.; Bruce, T. C. *J. Org. Chem.* **1992**, *57*, 1555.



reached. A closer approach of the porphyrin planes leads to van der Waals repulsion. Further, the dynamics calculation results reveal that the peripheral substituent (i.e., for structures 1–7 the substituent R) on the linker determines the size and the shape of the cavity between the two porphyrin cores. Both the steric and electronic effects of R play dominant roles in determining the global minimum structure. The larger R, the smaller the Ct–Ct distance. Thus, with 1 and 5, the Ct–Ct distance is shorter than with 4 (see Table I). Moreover, the more sp^3 character the bridging nitrogen displays, the more flexible the geometry, and hence, the Ct–Ct distance is shorter. The calculations show symmetrical dimers 1–5 to have D_4 symmetry with a small lateral shift. An exception is dimer 3 in which the global minimum structure exhibits a large lateral shift (Figure 2). This large lateral shift is brought about by two hydrogen bridges between adjacent amide side chains (Figure 3). Porphyrin 4 was found to be quite extended due to the bridging nitrogens being almost complete sp^2 centers. The arylsulfonate side-chain substituents seem to be best suited for effecting the smallest observed Ct–Ct distance. CHARM_m gas-phase calculations show *p*-toluenesulfonamide and *m*-pyridinesulfonamide (see 1 and 5) groups act similarly because they are essentially isosteric. Their bulky nature forces the linker units into optimally folded conformations, and the interplanar and center-to-center distances approach 5.0 Å. It is expected that the steric effect of *m*-pyridinesulfonamide and the corresponding *N*-methylpyridine derivative will be about the same, resulting in a similar calculated Ct–Ct distance for the corresponding dimers (1 and 2); however, the calculations show a larger Ct–Ct distance for 2 presumably due to the fact that its geometry in the gas phase exhibits a larger interplanar separation than the solution structure in order to disperse the positive charges more effectively.

Although CPK models show that very little free space exists between the porphyrin planes of 1, "breathing motion" observed in dynamics animations is expected to make possible the entry of small molecules into the cavity. Model building also establishes that the geometry for the global minimum calculated for 1 is well suited for binding a molecule of dioxygen to two cobalt atoms placed in the center of each porphyrin ring. The resulting complex, shown in Figure 4, has Co–O bond lengths of 1.8 Å, an O–O bond length of 1.4 Å (as in a peroxo complex⁵), and a Co–O–O bond angle of 149°. Such a complex has been invoked as an intermediate in the electroreduction reactions that cofacial porphyrin dimers catalyze.² The porphyrin cores in the unsymmetrical dimers 6 and 7 (Figure 5) were relatively slipped, being perturbed by the long and rigid carbonate leg. The symmetry in dimers 6 and 7 is reduced to approximate C_2 symmetry, and the Ct–Ct distances become larger as anticipated (5.52 Å for 6 and 5.36 Å for 7).

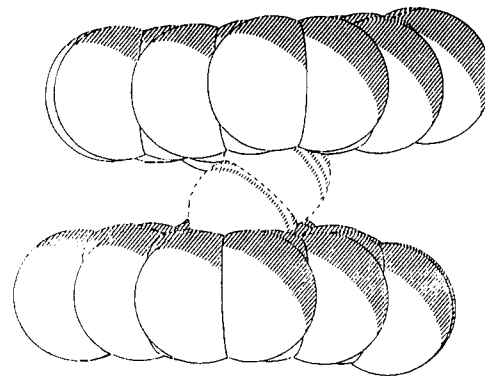


Figure 4. Hypothetical μ -peroxo bridged biscobalt porphyrin dimer 1 (protons, phenyl rings, and linkers omitted for clarity). Co–O distances are 1.8 Å; O–O distance is 1.4 Å. Co–O–O angle is 149°.

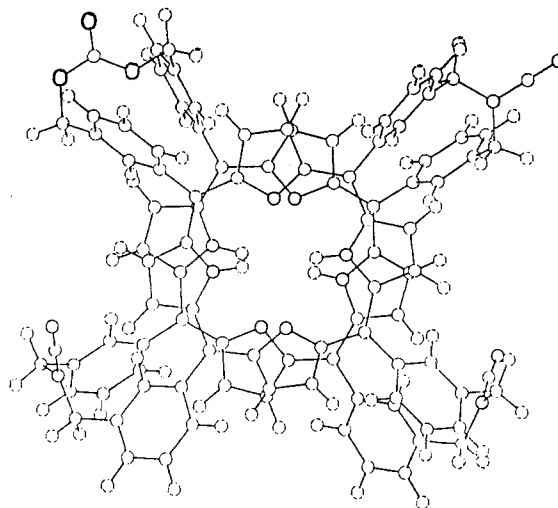
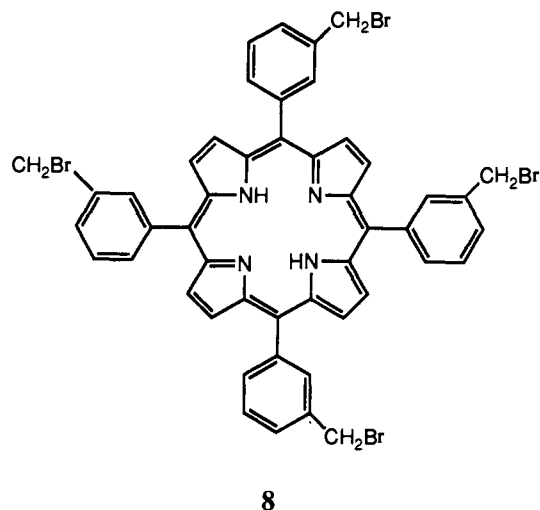


Figure 5. Top view of the CHARM_m-calculated global minimum structure for dimer 7.

Electroreduction of Dioxygen Catalyzed by Cofacial Biscobalt Tetraphenylporphyrin Dimers Studied at the Rotating Ring–Disk Electrode (RRDE). The cobalt dimeric porphyrins Co₂-1 to Co₂-4 and Co₂-6 were carefully evaporated onto the graphite disk electrode surface from DMF or CH₂Cl₂ solutions. After coating, the electrode was immersed into a dioxygen-saturated aqueous solution of 0.1 N H₂SO₄, and cyclic voltammograms were recorded to determine the potentials for the dioxygen reduction at the disk electrodes. Unfortunately, an estimation of formal potentials of the biscobalt porphyrins by this means was not feasible because voltammetric responses from the electrodes adsorbed with the cobalt porphyrins in the absence of dioxygen were not measurable. Our studies with adsorbed catalysts were, therefore, restricted to the voltammetric responses they produce in the catalytic reduction of dioxygen.

The catalytic peak potentials for the reduction of dioxygen at the disk electrode are summarized in Table II (see column 2). The dependence of peak potentials for dioxygen reduction on the nature of the cofacial biscobalt porphyrins is very slight. Further, the potentials were found to be comparable for monomeric cobalt porphyrin (Co-8) and cofacial biscobalt porphyrins. Electrochemical reduction of O₂ can occur at the disk electrode by a 2e⁻ process to yield H₂O₂ as an intermediate or via a 4e⁻ reduction to provide H₂O. In all experiments, the potential of the ring electrode was held at +1.1 V in order to detect the formation of H₂O₂. The fraction of dioxygen reduced to hydrogen peroxide was determined by the ratio of ring-to-disk currents and ring collection efficiency. RRDE voltammograms obtained from electrodes adsorbed with cobalt porphyrins Co-8, Co₂-6, and Co₂-2 are shown in Figure 6, and the derived electrochemical data are summarized in Table II. In the absence of cobalt porphyrins, no electrode reduction of dioxygen was observed within the range

(5) Scheidt, W. R.; Lee, Y. J. *Structure Bonding* 1987, 64, 1–71.



of potentials shown in Figure 6.

Electrochemical results with porphyrin electrodes in aqueous solutions containing 1 mM hydrogen peroxide in the absence of dioxygen establish that biscobalt porphyrin dimer **2** catalyzes the electroreduction or disproportionation of hydrogen peroxide. The intercept value of the Koutecky–Levich plot at the electrode adsorbed with Co₂-**2** as a catalyst is larger than that for dioxygen reduction. This indicates that the reduction rate of H₂O₂ is smaller than that of dioxygen and excludes unbound hydrogen peroxide as an intermediate in the reduction of dioxygen to water.

Koutecky–Levich plots of I_{lim}^{-1} (I_{lim} , limiting current density) vs $\omega^{-1/2}$ (ω , the rotation rate) for dioxygen reduction measured at rotating graphite disk electrodes adsorbed with the cobalt porphyrins are shown in Figure 7 along with the calculated lines for 2e⁻ and 4e⁻ reductions. An excellent linearity is observed between I_{lim}^{-1} and $\omega^{-1/2}$. Values of I_{lim} for the catalyzed reduction are expressed by the Koutecky–Levich equation⁷ (eqs 1 and 2),

$$1/I_{\text{lim}} = 1/I_{\text{lev}} + 1/I_{\text{kin}} \quad (1)$$

$$I_{\text{lev}} = 0.2nFD^{2/3}v^{-1/6}C_0\omega^{1/2} \quad (2)$$

where I_{lev} is the limiting current density when the reaction is totally mass transfer controlled and I_{kin} is the kinetic current. The number of electrons transferred, n , is calculated from the slope of the Koutecky–Levich plot using the following values: v is the kinematic viscosity of the electrolyte solution, 0.01 cm²/s; D is the diffusion coefficient of dioxygen, 1.7×10^{-5} cm²/s; C_0 is the concentration of dioxygen, 1.2 mM. The n values calculated from the slopes of Koutecky–Levich plots are slightly different from those obtained from the ratio of ring-to-disk limiting currents (see column 5 in Table II). This discrepancy seems to arise from the small collection efficiency during the oxidation of hydrogen peroxide at the ring electrode.^{1c} The rate of the chemical reaction of the reduced cobalt porphyrins and O₂ was determined from the intercept of Koutecky–Levich plots by eq 3, where k is the

$$I_{\text{kin}} = nk\Gamma_{\text{dimer}}FC_0 \quad (3)$$

rate constant for the catalyzed reduction and Γ_{dimer} is the concentration of cofacial biscobalt porphyrin dimer on the electrode surface. The surface concentration of a catalyst (2×10^{-10} mol cm⁻²) on the disk electrode is estimated from the amount of cobalt porphyrin in a small volume of stock solution and the electrode surface area. Using the method of Collman and co-workers,^{1h} who showed that the reduction of dioxygen is first order in catalyst and dioxygen, the second-order rate constant for electroreduction of dioxygen in the presence of the biscobalt porphyrin dimers was calculated to be $(2 \pm 1) \times 10^5$ M⁻¹ s⁻¹. This value differs slightly along the series of the biscobalt porphyrin catalysts employed.

Examination of Table II reveals that all the biscobalt porphyrin dimers studied catalyze the reduction of dioxygen at the graphite disk electrode. The magnitude of the disk limiting current and the fraction of dioxygens which undergo 2e⁻ and 4e⁻ reduction

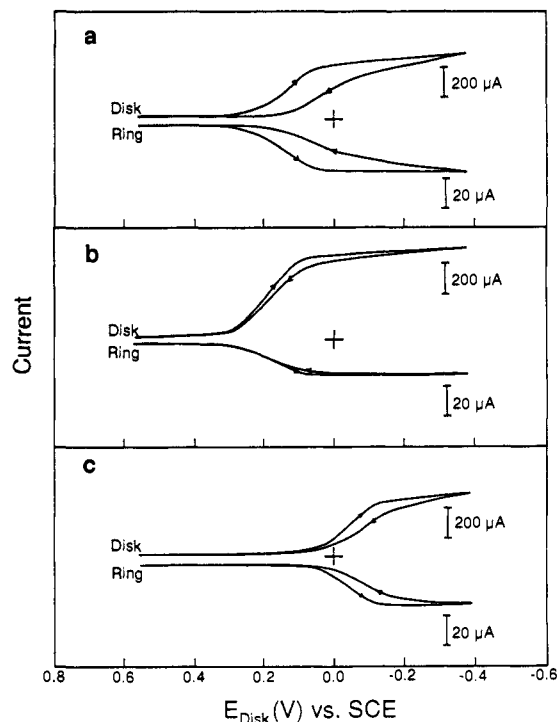


Figure 6. Ring-disk current-potential curves for dioxygen reduction at electrodes adsorbed with cobalt porphyrins in 0.1 N H₂SO₄ aqueous solutions saturated with O₂ at 1 atm. Scan rate (v) 20 mV/s. Ring potential 1.1 V vs SCE. Rotation rate (ω) 100 rpm. (a) Monomeric cobalt porphyrin **8**; (b) dimeric cobalt porphyrin **2**; (c) dimeric cobalt porphyrin **6**.

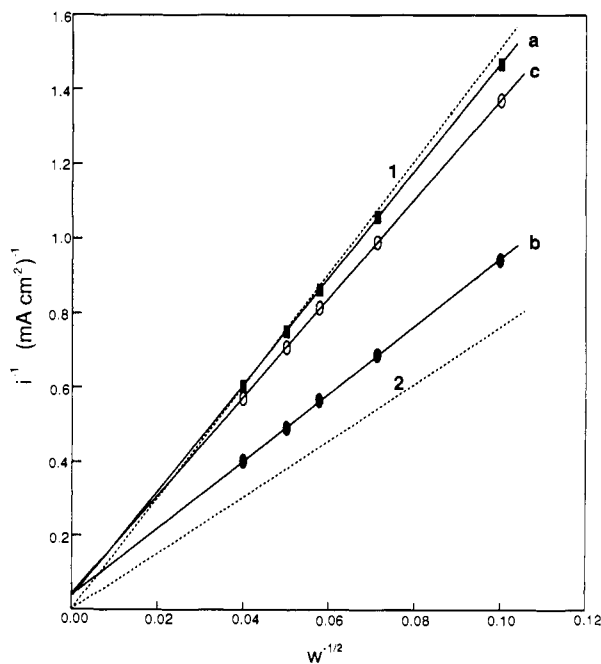


Figure 7. Koutecky–Levich plots for O₂ reduction catalyzed by cobalt porphyrins in 0.1 N H₂SO₄ aqueous solutions saturated with O₂ at 1 atm. The dashed lines (1 and 2) were calculated for the diffusion-convection limited reduction by two and four electrons, respectively. (a) Monomeric cobalt porphyrin **8**; (b) dimeric cobalt porphyrin **2**; (c) dimeric cobalt porphyrin **6**.

depend on the nature of the biscobalt porphyrin dimer. As expected, O₂ reduction catalyzed by the monomeric porphyrin Co-**8** mainly occurs through the 2e⁻ reduction pathway, resulting in the formation of hydrogen peroxide. The unsymmetrical biscobalt porphyrin dimer **6** shows monomer-like catalytic activity. The similarity between **6** and the monomeric porphyrin is attributed

Table I. ^1H NMR and UV/Visible Spectral Data and CHARM_m-Calculated Properties^a of Quadruply Linked Dimers

compd	Ct-Ct ^e	P-P ^e	LS ^e	^1H NMR			UV/vis
				δ N-H ^b	δ' N-H ^c	δ H-2' ^b	λ ^d
1	5.03	5.00	0.28	-4.34	-5.4 ^f	7.04	18.9
2 ^f	5.60	5.54	0.27		-5.8 ^f		
3	5.15	4.39	2.69		-4.35	6.95 ^c	20.0
4	5.75	5.73	0.20	-3.98	-4.0	7.31	18.1
5	5.03	4.99	0.67	-4.42		7.14	19.1
6 ^f	5.52	5.32	1.46	-3.95	-3.95		19.0
7 ^f	5.36	5.35	0.34	-3.80			17.0
8				-2.81		8.21	12.0

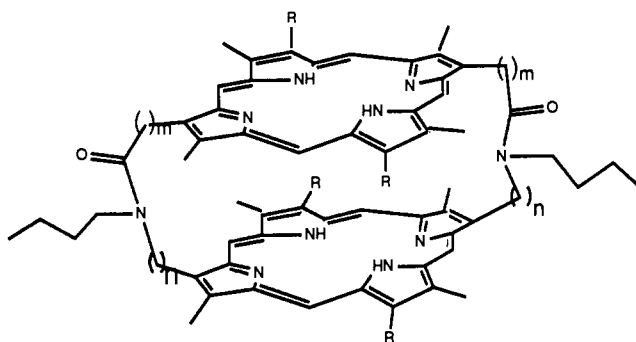
^aAll distances are in Å. ^bChemical shifts in ppm relative to TMS. Solvent used is CDCl_3 unless otherwise indicated. ^cSolvent used is $\text{DMSO}-d_6$. ^dSoret bandwidth at half-height in nm. ^eCt-Ct is the center-to-center distance, P-P is the interplanar distance, and LS is the lateral shift (see Figure 2). ^fThese have more than one H-2' resonance. ^gChemical shift was determined at 150 °C in $\text{DMSO}-d_6$.

Table II. Dioxygen Electrocatalytic Properties at Electrodes Adsorbed with Cobalt Tetraphenylporphyrins

porphyrin	$E_{p,\text{cat}}^a$	% H_2O_2 (n) ^b	I_{lim}^c	n^d
Co ₂ -1	+0.10	34.0 ± 3.0 (3.3)	0.94	3.1 ± 0.2
Co ₂ -2	+0.11	30.1 ± 3.0 (3.4)	1.06	3.3 ± 0.2
Co ₂ -3	+0.04	51.8 ± 3.0 (3.0)	0.76	2.5 ± 0.2
Co ₂ -4	+0.08	51.1 ± 3.0 (3.0)	0.78	2.6 ± 0.2
Co ₂ -6	-0.12	68.7 ± 5.0 (2.6)	0.72	2.3 ± 0.2
Co-8	+0.07	69.8 ± 5.0 (2.6)	0.69	2.1 ± 0.2

^aDioxygen electrocatalytic peak potential ($E_{p,\text{cat}}$ vs SCE) at graphite disk electrode at scan rate 0.1 V s⁻¹. ^bCalculated from % $\text{H}_2\text{O}_2 = (-i_r/Ni_d)100$ where i_r and i_d are the ring and disk limiting currents, respectively, and N is the collection coefficient. The number of electrons transferred (n in parentheses) is calculated from $n = 4 - 2(i_r/Ni_d)$. ^cLimiting current density (mA cm^{-2}) for the reduction of dioxygen at 100 rpm in O_2 -saturated solutions. ^dEvaluated from the slopes of Koutecky-Levich plots for dioxygen reductions with the catalysts.

to the long Ct-Ct distance in Co₂-6 (above 5.3 Å) precluding any effective coordination of O_2 to effect the $4e^-$ reduction of O_2 to water. It should be noted that the inability of biscobalt porphyrins with extended Ct-Ct distances to carry out $4e^-$ reduction of O_2 has previously been observed.¹ For example, Collman and associates showed that porphyrin dimers A and B with long Ct-Ct



- A $n = 3, m = 2, R = \text{hexyl}$
 B $n = 3, m = 1, R = \text{hexyl}$
 C $n = 2, m = 1, R = \text{hexyl}$

distances (6.4 and 5.4 Å, respectively) are not effective in reducing oxygen to water, whereas the porphyrin dimer C with a Ct-Ct distance of 4.2 Å is very effective.^{1b}

Of the porphyrins examined in this study, the water-soluble symmetrical cofacial biscobalt porphyrin Co₂-2 and its precursor, porphyrin Co₂-1, show the greatest $4e^-$ reduction activity as shown in the increased disk limiting currents and the decreased detection of hydrogen peroxide (less than 34%). The Ct-Ct distances of Co₂-1 and Co₂-2 are the shortest (less than 5 Å)⁶ of the dimeric

(6) The CHARM_m-calculated interplanar distance for dimer 7 is 5.54 Å. This overestimated value is due to the failure of CHARM_m in handling cationic structures. Therefore, the interplanar distance or the center-to-center distance was estimated from eqs 5 and 7 and was found to be 4.75 Å.

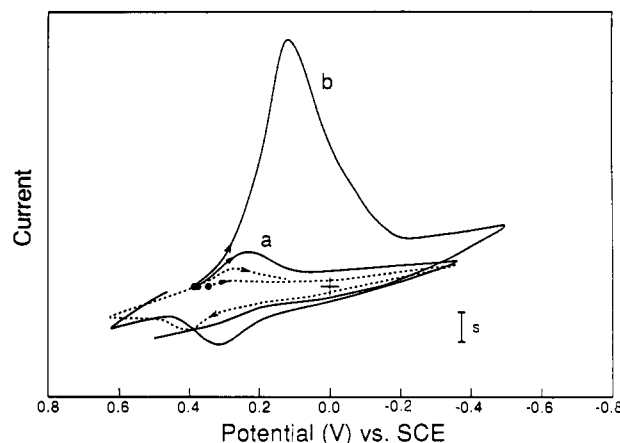


Figure 8. Cyclic voltammograms at the pyrolytic graphite disk electrode in dissolved cofacial cobalt porphyrin 2. (a) Solution saturated with argon, $s = 20 \mu\text{A}$; (b) solution saturated with dioxygen, $s = 100 \mu\text{A}$. Scan rate 0.1 V/s; supporting electrolyte 0.1 N H_2SO_4 . The dashed line is the background response of the pyrolytic graphite when porphyrin is absent.

porphyrins studied.

Electrochemical studies of the reduction of O_2 by the water-soluble Co₂-2 dissolved in acidic aqueous solution, measured under argon at a highly polished pyrolytic graphite electrode, are shown in Figure 8a. As in the case of the RRDE experiments with porphyrin dimers, the solutions were 0.1 N in H_2SO_4 and contained 0.5 mM Co₂-2. The redox couple for Co₂-2 in the absence of O_2 has broadened waves, implying that the two cobalt(III) centers are reduced in a stepwise manner at very close potentials. A half-wave potential ($E_{1/2}$) value of +0.29 V vs SCE was obtained by averaging the cathodic and anodic peak potentials. Repetitive scanning produces identical voltammograms, indicating that the oxidation states of the cobalt can be reversibly changed between Co(III) and Co(II). The cathodic peak current ($i_{p,c}$) is equal in magnitude to the anodic peak current ($i_{p,a}$) in thoroughly deoxygenated solutions of cofacial cobalt porphyrin 2. Upon the addition of a small amount of dioxygen, $i_{p,c}$ is increased while $i_{p,a}$ is decreased.

To investigate the effect of Co₂-2 on the reduction of dioxygen, cyclic voltammetry was performed in dioxygen-containing solutions of Co₂-2. The cyclic voltammogram obtained for Co₂-2 in the absence of dioxygen is comparable to that obtained in the presence of dioxygen (see Figure 8). The foot of wave a in Figure 8 is close to the potential where the catalytic reduction of dioxygen (wave b) begins in oxygen-saturated solutions of Co₂-2. The catalytic peak potential for the reduction of dioxygen is +0.11 V, which is the same as the value obtained with a electrode doped with Co₂-2. The potentials for electrochemical reduction of O_2 remain

(7) (a) Koutecky, J.; Levich, V. G. *Zh. Fiz. Khim.* **1958**, *32*, 1565. (b) Andrieux, C. P.; Dumas-Bouchiat, J. M.; Savieant, J. M. *J. Electroanal. Chem.* **1982**, *131*, 1. (c) Bard, A. J.; Faulkner, L. R. *Electrochemical Methods, Fundamentals and Applications*; Wiley: New York, 1980; Chapter 6.

the same regardless as to whether catalyst Co₂-2 is free in solution or fixed at the disk of a RRDE. The fraction of dioxygen reduced to hydrogen peroxide is 29 ± 3% detected at the ring. Repetitive scanning results in a very small decrease of disk limiting current (5% decrease in 10 repetitive scans). The number of electrons transferred, $n = 3.2 \pm 0.1$, obtained from the slope of the Koutecky-Levich plot indicates 60 ± 5% electroreduction of dioxygen to water, even after prolonged exposure.

Correlations between the Interplanar Distance and Physical and Electrochemical Properties of the Free Base Forms of the Porphyrin Dimers. Considering the UV/vis spectra of bisporphyrins, it has been shown that the magnitude of exciton coupling, as it is reflected by the broadening of the Soret absorption, is determined by the closeness of the two porphyrin cores^{4,8} (see Table I). This is supported by the linear relationship which we find between the width of the Soret absorption (W) and the gas-phase calculated interplanar distances (P-P) (see Table I and eq 4). As it is shown

$$P-P = -0.70W + 18.45 \quad R = 0.94 \quad (4)$$

in eq 4, the values of the Soret band width are large when the two porphyrin cores in the dimer are in close proximity (short interplanar distance). Thus, from eq 4 the increase in the bandwidth of the Soret absorption serves as a good index for the estimation of the closeness of the two porphyrin cores. The ¹H NMR spectra of the porphyrin dimers 1-7 display resonances that are significantly upfield shifted when compared to those of the corresponding monomeric porphyrin **8** (Table I). The upfield shift in the chemical shifts of the pyrrolic N-H resonances is about 2.5 ppm and that of ortho phenylic H (H-2') resonances is about 1.3 ppm (see Table I). As anticipated, the gradual upfield shift of the pyrrolic N-H resonances and ortho phenylic H in the series of the dimers studied (Table I) results from a decrease in separation between the two porphyrin rings; one porphyrin core experiences more of the shielding effect of the other as it comes closer to its shielding region.⁷ Further, the CHARM_m-calculated interplanar distances (P-P) of porphyrin dimers 1-7 (see Table I) have been shown to correlate reasonably well with the ¹H NMR chemical shifts of the pyrrolic N-H (δ N-H) and the ortho phenylic H resonances (δ H-2') eqs 5 and 6 respectively.⁴

$$P-P = 0.88(\delta \text{ N-H}) + 8.85 \quad R = 0.96 \quad (5)$$

$$P-P = 3.41(\delta \text{ H-2}') - 19.20 \quad R = 0.96 \quad (6)$$

Comparison of the slopes of eqs 5 and 6 indicates that the H-2' resonances experience more of the shielding effect of the magnetic anisotropy of the two porphyrin rings than that of the pyrrolic N-H. This is in good agreement with CHARM_m-calculated global minima structures of 1-5 which show the ortho phenylic protons (H-2') to be more directed into the shielding cone of the porphyrin cores than the pyrrolic N-H protons, and the average distance between the H-2' protons and the plane of the opposite porphyrin ring is considerably shorter (4 Å) than the interplanar distances (around 5 Å).

A linear correlation exists between ¹H NMR chemical shifts of the N-H resonances (δ' N-H) of DMSO-*d*₆ solutions of the dimers (Table I) and the number of electrons (Table II) transferred (n) in the reduction of dioxygen catalyzed by their corresponding biscobalt porphyrin derivatives (eq 7 and Figure 9).

$$\delta' \text{ N-H} = -1.94n + 0.67 \quad R = 0.96 \quad (7)$$

As previously mentioned, the N-H resonances (δ' N-H) correlate reasonably well with the calculated gas-phase interplanar distance (see eq 5). Thus, the percentage of the 4e⁻ reduction of O₂ is high for the dimers having interplanar distances of 5 Å such as **1** and **2**, whereas for those having long interplanar distances (above 5.3 Å) such as **4** the percentage of the 2e⁻ reduction is dominant.

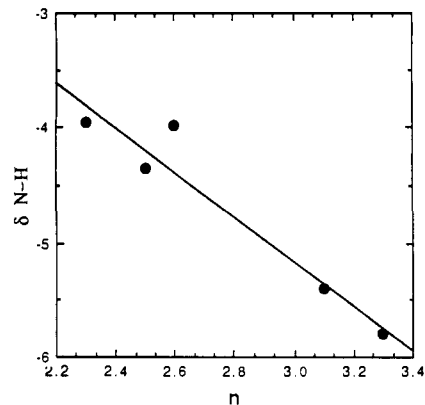


Figure 9. Plot of the ¹H NMR chemical shifts of the N-H resonances of the porphyrin dimers in DMSO-*d*₆ δ' N-H vs the number of electrons transferred (n) in the reduction of dioxygen catalyzed by their biscobalt derivatives.

Summary and Conclusions

Linear relationships are observed between the ¹H NMR chemical shifts of pyrrolic N-H and both the gas-phase calculated interplanar distances and the number of electrons transferred (n) in the reduction of dioxygen catalyzed by biscobalt porphyrin dimers. The electrochemical results show that biscobalt porphyrin dimers Co₂-1 to Co₂-4 and Co₂-6 bind dioxygen and consequently reduce it via two different paths: through 4e⁻ reduction to form water and via 2e⁻ reduction to give hydrogen peroxide. The linear relationship observed between the solution ¹H NMR chemical shift of N-H and the number of electrons transferred (n) in the dioxygen reduction indicates that the interplanar distance in the dimers is a crucial factor for determining the electroreduction pathway. Biscobalt porphyrin dimers with appropriate interplanar distances and high field N-H chemical shifts catalyze the reduction of dioxygen mainly through the 4e⁻ pathway, whereas those with long interplanar distances and low field N-H chemical shifts do via the 2e⁻ path. The finding that the reduction rate of dioxygen to water is greater than that of hydrogen peroxide excludes the intermediacy of the latter in these processes. In contrast to the observations¹ of Collman and Chang, the peak potentials for oxygen reductions for the series of biscobalt dimers are generally comparable to those of monomeric species, which are not capable of four-electron reduction to water; therefore, it is believed that the precise structure of the dimeric species is the dominant factor governing the catalytic properties of these systems. The following remarks emerge from this study: (1) The precise geometrical nature of the biscobalt tetraphenylporphyrin dimers, and not their catalytic peak potentials, appears to be the crucial factor determining their activity in the 4e⁻ reduction of oxygen to water. (2) The dimeric porphyrins presented herein represent the first effective rigid water- and non-water-soluble porphyrin dimer system to catalyze 4e⁻ reduction of dioxygen to water.

Experimental Section

General. Absorption spectra were recorded on a Cary-14 spectrophotometer interfaced to a Zenith computer equipped with OLIS (On-Line Instrument System Inc.) data acquisition and processing software. Fast atom bombardment (FAB) mass spectroscopy was performed at UCSB using *m*-nitrobenzyl alcohol as the matrix and a parallel run of cesium rubidium iodide as the reference. All reactions were carried out with purified reagents in dry, purified solvents. Column chromatography was performed with Fischer Type 60-Å (200-425-mesh) silica gel. Preparative thin-layer chromatography (TLC) was performed using E.M. Sciences Kieselgel 60 F₂₅₄.

Electrochemistry. Cyclic voltammetric measurements were performed with a three-electrode potentiostat (Bioanalytical Systems, Model CV-27) and were recorded on Houston Instruments Model 100 Omnigraphic. A platinum wire electrode separated from the analyte compartment by a medium porosity glass frit was used as the auxiliary electrode. A Ag/AgCl electrode, filled with aqueous tetramethylammonium chloride solution and standardized to 0.00 V vs SCE with a solution junction via a Pyrex glass tube closed with a soft glass cracked bead contained in a luggin capillary, was used as the reference electrode. A pyrolytic graphite

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(0.46-cm²) disk electrode was employed as the working electrode. Rotating ring-disk experiments were conducted using a RDE4 instrument (Pine Instrument Company). A pyrolytic graphite disk/platinum ring electrode was used. The ring collection efficiency ($N = 0.17$) was determined using a solution of ferrocene. All working electrode surfaces were highly polished with alumina paste prior to each experiment. Adsorption of metalloporphyrins was accomplished by dropping organic solvents containing metalloporphyrins on the disk electrode, followed by careful evaporation of the solvent. Aqueous solutions of water-soluble porphyrins were prepared using distilled-deionized water with less than 0.5% *N,N*-dimethylformamide (DMF). Dioxygen concentrations in O₂-saturated solutions were assumed to be 1.2 mM at room temperature. Solutions of 0.1 N H₂SO₄ were used as supporting electrolytes. All reported potentials are with respect to a saturated calomel electrode (SCE).

Theoretical Calculations. All model building and calculations were performed on a Silicon Graphics IRIS 4D/220 GTX workstation, using the programs Quanta version 3.2 (Polygen Corp.) and CHARM_m³ version 21.2. The topology file PORPHYRIN.HRTF supplied by Polygen was used as a basis for the porphyrin moieties of the dimers, and the linkers were constructed in Chemnote, the 2D modeling facility in Quanta. Minimization was performed using the steepest descent algorithm, followed by an adopted basis Newton-Raphson algorithm, until the energy change tolerance was less than 10⁻⁹ kcal/mol. The nonbonded interaction cutoff distance and hydrogen bonding cutoff distance were chosen to be 11.5 and 7.5 Å, respectively. Molecular dynamics were performed using Verlet integration and the SHAKE algorithm to fix C-H bonds. At 600 K, the maximum allowable fluctuation in temperature was fixed at 25 K. Nonbonded interaction and hydrogen bond lists were updated every 0.05 ps.

Preparation of Co₂-1. A mixture of 1⁹ (20 mg, 0.0102 mmol) and CoCl₂·6H₂O (100 mg, 0.42 mmol) was heated at 135 °C for 5 h and then diluted with chloroform (100 mL) and methanol (25 mL). The reaction mixture was extracted with 5% aqueous ammonium hydroxide solution, water, and brine, and the organic layer was separated, dried over anhydrous Na₂SO₄, filtered, and evaporated to give 19 mg (90.4%) of Co₂-1 as a deep orange powder: FABMS m/z 2071 (calcd for C₁₁₆H₈₀N₁₆O₈S₄Co₂ [M⁺] m/z 2070.5); UV/vis (DMF) λ_{\max} ($\epsilon \times 10^{-3}$ cm⁻¹ M⁻¹) 409 (121), 529 (17.7).

Preparation of Co₂-2. A mixture of 2⁹ (10 mg, 0.0049 mmol) and CoCl₂·6H₂O (50 mg, 0.21 mmol) in DMF (5 mL) was heated at 135 °C for 6 h. The reaction mixture was evaporated, and the resulting green residue was triturated with cold water, filtered, washed with ether, and dried to give 9.8 mg (93.3%) of Co₂-2 as a deep orange powder: FABMS

m/z 2115 (calcd for C₁₁₉H₈₉N₁₆O₈S₄Co₂ [M⁺ - CH₃] m/z 2115.5); UV/vis (DMF) λ_{\max} ($\epsilon \times 10^{-3}$ cm⁻¹ M⁻¹) 409 (300), 530 (28.3).

Preparation of Co₂-3. A mixture of 3⁹ (10 mg, 0.0064 mmol) and CoCl₂·6H₂O (50 mg, 0.21 mmol) in DMF (20 mL) was heated at 120 °C for 48 h. The reaction mixture was evaporated to dryness, and the reddish residue was triturated with water (100 mL × 3), collected, washed with ether, and dried at 25 °C/0.2 mmHg to give 9.2 mg (85.7%) of Co₂-3 as a reddish powder: FABMS m/z 1678 (calcd for C₁₀₀H₇₂N₁₆O₄Co₂ (M⁺) m/z 1678.5); UV/vis (DMF) λ_{\max} ($\epsilon \times 10^{-3}$ cm⁻¹ M⁻¹) 409 (267), 529 (17.8).

Preparation of Co₂-4. A mixture of 4⁹ (18 mg, 0.012 mmol) and CoCl₂·6H₂O (50 mg, 0.21 mmol) in DMF (10 mL) was heated at 95 °C for 8 h and then diluted with chloroform (100 mL). The reaction mixture was extracted with water and brine, dried over anhydrous Na₂SO₄, filtered, and evaporated to yield a deep orange powder. The resulting orange residue was subjected to silica gel column eluting with a mixture of chloroform/methanol (100:3). The nonpolar orange band was collected to give 17 mg (87.6%) of Co₂-4 as a deep orange powder: UV/vis (CHCl₃) λ_{\max} ($\epsilon \times 10^{-3}$ cm⁻¹ M⁻¹) 406 (320), 530 (27.7); FABMS m/z 1607 (calcd for C₁₀₀H₆₄N₁₆Co₂ [M⁺] m/z 1606.4).

Preparation of Co₂-6. A mixture of 6⁹ (10 mg, 0.0054 mmol) and CoCl₂·6H₂O (50 mg, 0.21 mmol) in DMF (30 mL) was heated at 120 °C for 48 h and then diluted with chloroform (200 mL). The reaction mixture was extracted with water and brine, dried over anhydrous Na₂SO₄, filtered, and evaporated to yield 9.7 mg (91.5%) of Co₂-6 as a deep orange powder: FABMS m/z 1974 (calcd for C₁₁₂H₇₆N₁₄O₃S₃Co₂ [M⁺] m/z 1974.4); UV/vis (DMF) λ_{\max} ($\epsilon \times 10^{-3}$ cm⁻¹ M⁻¹) 410 (209), 530 (16.7).

Preparation of Co-8. A mixture of 8^{8b} (50 mg, 0.051 mmol), CoCl₂·6H₂O (100 mg, 0.42 mmol), and NaBr (1 g) in DMF (20 mL) was heated at 80 °C for 24 h and then diluted with chloroform (200 mL). The reaction mixture was extracted with water and brine, and the organic layer was separated, dried over anhydrous Na₂SO₄, filtered, and evaporated to yield an orange powder. The resulting orange residue was subjected to silica column eluting with a mixture of chloroform/methanol (100:3). The nonpolar band was collected to give 28 mg (53%) of Co-8 as deep orange powder: UV/vis (CHCl₃) λ_{\max} ($\epsilon \times 10^{-3}$ cm⁻¹ M⁻¹) 410 (151), 528 (20.5); FABMS m/z 1039 (calcd for C₄₈H₃₂Br₄N₄Co [M⁺] m/z 1038.9).

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Registry No. 1, 134260-60-9; Co₂-1, 141090-89-3; 2, 134209-10-2; Co₂-2, 141090-90-6; 3, 138312-89-7; Co₂-3, 141090-91-7; 4, 133672-00-1; Co₂-4, 141090-92-8; 5, 133671-99-5; 6, 138312-91-1; Co₂-6, 141090-93-9; 7, 138312-92-2; 8, 133671-91-7; Co-8, 141090-94-0; O₂, 7782-44-7.

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Communications to the Editor

An Alternate Geometry for the Catalytic Triad of Serine Proteases

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The catalytic triad of serine proteases, Asp-His-Ser, is one of the classic motifs of enzymology. Effective strategies for the incorporation of the triad into non-protease protein scaffolds (i.e., antibodies¹ or de novo designed peptides²) might allow the de-

velopment of sequence-specific peptidases or other novel enzymes. Such catalyst design would be facilitated by knowledge of the limits within which the orientation or composition of the triad members can be altered while still preserving significant peptidase activity.

We have previously reported that, of the three members of the triad, only the serine in trypsin is necessary for a minimal level of catalysis toward peptide bonds.³ In this communication we report the mutation of Asp 102 and the partial replacement of its function in catalysis through the introduction of aspartic or glutamic acid in place of a neighboring amino acid, Ser 214. The

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