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Quinone-Substituted Monometalated Porphyrin Dimers: Models for Photoinduced Charge Separation at Fixed Orientation and Energy

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Among the most significant issues currently being debated in the area of photosynthesis are those that concern the role that interchromophore interactions[1] play in the initial charge separation process.[2-11] In recent years a number of model compounds have been prepared[12] in an effort to understand natural photosynthetic systems. The models reported to date,[13-15] however, have nearly all consisted of a simple monomeric porphyrin covalently linked to one[12] or more[16] redox active groups and as a result have provided little insight into how interchromophore interactions might influence multistep photoinduced electron transfer reactions.[12e,14b,16]

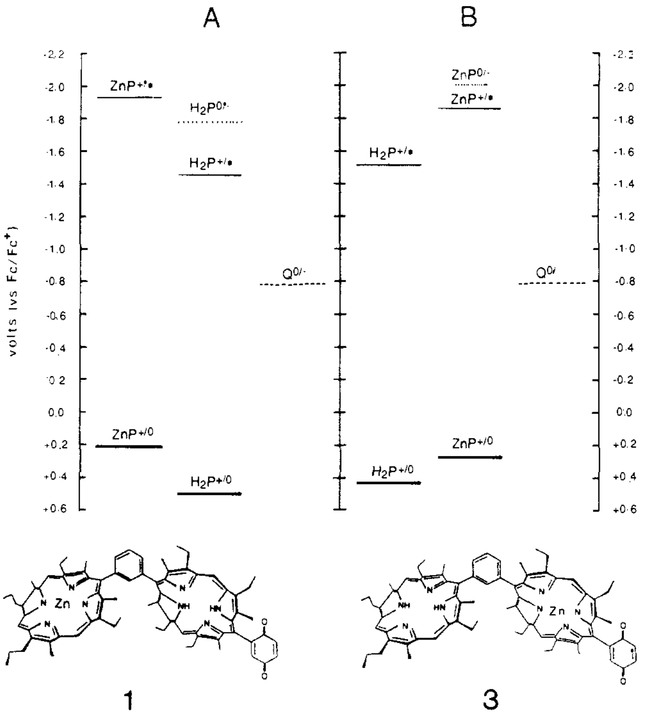

Figure 1. Ground and excited state redox potentials (volts versus ferrocene/ferricinium) for dimers **1** (frame A) and **3** (frame B). Symbol $Q^{0/-}$ (- - -) represents the redox potential (cyclic voltammetry, dichloromethane, 0.2 M tetrabutylammonium tetrafluoroborate) for quinone reduction in **1** and **3**. The symbols $ZnP^{+/0}$ and $H_2P^{+/0}$ (—) represent the measured redox potentials for oxidation of the zinc and free-base subunits of **1** and **3**. Symbols $ZnP^{0/-}$ and $H_2P^{0/-}$ (...) represent the corresponding reductions for the bis-zinc and free-base quinone-free "gable" porphyrins reported earlier.[19] (We consider these values more appropriate since coulombic effects from the reduced quinone shift the corresponding potentials in **1** and **3**; no coulombic corrections were made, or appeared warranted, for $ZnP^{+/0}$ and $H_2P^{+/0}$.) Symbols $H_2P^{+/*}$ and $ZnP^{+/*}$ (—) indicate the observed lowest singlet energies (obtained by the method of Netzel[24a]) of these same free-base and bis-zinc quinone-free "gable" porphyrins (1.96 and 2.13 eV, respectively) plotted relative to the redox potentials $H_2P^{+/0}$ and $ZnP^{+/0}$ mentioned above.

We have therefore prepared a new series of photosynthetic models: the selectively metalated, quinone-substituted "gable" and "flat" dimers **1–4**.[17] Compounds **1–4** contain the key biomimetic components, metalloporphyrin (ZnP), free-base porphyrin (H_2P), and quinone (Q), held in several well-defined configurations. They provide the first "matched set" of photosynthetic models suitable for studying interchromophore orientation and energetic effects.[20]

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(17) The monoquinone-substituted dimers **5** and **6** (and the monomers **9** and **11**) were prepared from dipyrrolic intermediates[18] with a modification of the methods we have reported earlier.[13,19] Zinc insertions were effected in a regioselective manner at the hydroquinone and quinone oxidation levels to give, following retreatment with DDQ and chromatographic purification, respectively the "proximal" and "distal" monometalated quinones. ^{1}H NMR spectroscopy was used to make the regiochemical assignments.

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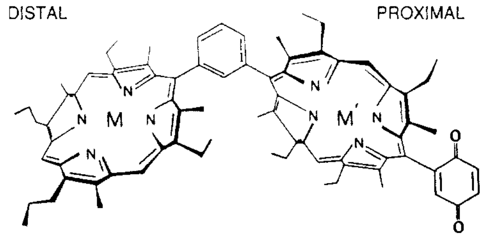
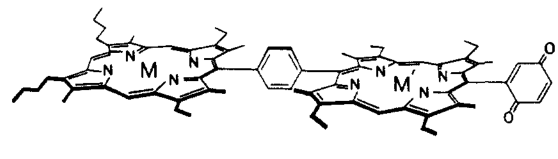
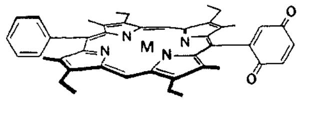


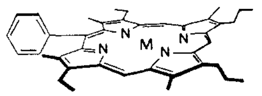
1. M = Zn, M' = 2H
3. M = 2H, M' = Zn
5. M = M' = 2H
7. M = M' = Zn



2. M = Zn, M' = 2H
4. M = 2H, M' = Zn
6. M = M' = 2H
8. M = M' = Zn



9. M = 2H
10. M = Zn



11. M = 2H
12. M = Zn

The center-to-center distances between the unsubstituted "distal" porphyrin (MP_d) and the quinone are estimated, on the basis of CPK models, to be 14 Å in the "gable" series and 20 Å in the "flat" compounds. Similarly, the center-to-center distances between the "distal" and "proximal" porphyrin subunits (MP_p) are estimated to be 10.5 and 12.5 Å in the "gable" and "flat" series, respectively. Two different energetic arrangements are also defined in compounds **1**–**4**. Figure 1 shows the ground and excited state redox potentials for the localized H_2P, ZnP, and Q subunits in **1** and **3**. In compound **1** (and **2**), an energy gradient exists for net electron transfer from the photoexcited "distal" porphyrin, ZnP_d^*, through $H_2P_p^*$ (or $H_2P_p^-$) to Q (frame A). In model **3** (and **4**), on the other hand, the "proximal" ZnP_p porphyrin forms an energy barrier between $H_2P_d^*$ and Q (frame B).

The electronic spectra of compounds **1**–**8** suggest that the two chromophores do not act entirely as independent light absorbing entities. Rather, as has been observed in other "gable" and "flat" dimers,[13,19,21,22] the two subunits are dipole–dipole coupled, with the degree of coupling being somewhat greater in the "gable" series. For instance, while the control monomer **10** shows only one sharp Soret band at 414 nm, the Soret band of the "gable" dimer **7** is split into two peaks of nearly equal intensity (λ_{max} = 407 nm, 424 nm). The "flat" compound **8** shows a single strong Soret peak that is red-shifted by 10 nm relative to **10** (λ_{max} = 424 nm) and has a slight shoulder at higher energy (λ_{max} = 412 nm). Similar but less dramatic effects are seen for the monometalated dimers **1**–**4** (c.f. Supplementary Material).

Table I. Fluorescence Properties of Quinone-Substituted Dimers and Control Compounds[a]

compd	emission maxima (nm)		Φ_F[b]	k_{ET}[c] (s^{-1})
1	d	d	≤1 × 10^{-5}	≥10^{12}
2	587	637	3.5 × 10^{-5}	≃10^{12}
3	642	705	1.7 × 10^{-4}	5.4 × 10^{10}
4	632	702	7.7 × 10^{-4}	1.1 × 10^{10}
5	d	d	≤1 × 10^{-5}	≥7.5 × 10^{11}
6	632	701	3.9 × 10^{-4}	2.2 × 10^{10}
7	d	d	≤1 × 10^{-5}	≥10^{12}
8	585	636	2.3 × 10^{-5}	≥10^{12}
9	d	d	≤1 × 10^{-5}	≥7.5 × 10^{11}
10	d	d	≤1 × 10^{-5}	≥10^{12}
11	630	697	1.3 × 10^{-1}	
12	577	630	3.0 × 10^{-2}	

[a] Measured at room temperature in dilute toluene solutions (<5 × 10^{-7} M) of equal optical density with excitation at the Soret maximum. [b] Quantum yields were measured relative to H_2TPP (tetraphenylporphyrin).[29] We estimate an uncertainty of ±10% for these values. [c] Estimated by the method of Joran et al.[12a] with values of $\Phi_F = 0.090$ and 0.11 and $\tau_S = 10 \times 10^{-9}$ and 13×10^{-9} s for the previously reported[13,19] unsubstituted free-base "gable" and "flat" dimers, respectively, and values of $\Phi_F = 0.045$ and 0.051 and $\tau_S = 1.5 \times 10^{-9}$ and 1.5×10^{-9} s for the corresponding bis-zinc complexes. [d] Emission for these samples could not be detected.

As shown in Table I, the emission intensities of dimers **1**–**8** (and monomers **9** and **10**) are all substantially quenched in comparison to the control monomers **11** and **12** (or the unsubstituted "gable" and "flat" dimers reported earlier[13]).[23] To a first approximation, therefore, net electron transfer quenching[12,24] from the porphyrin dimer to the quinone is fast compared to the rate of fluorescence emission.[25] Using analyses identical with those employed for monomeric porphyrins,[12a] a net electron transfer rate (k_{ET}) representing the sum of all processes leading to increased fluorescence quenching may be estimated for compounds **1**–**8** (Table I).

The data in Table I show that both interporphyrin orientation and energetic effects influence the net electron transfer quenching rate. Firstly, within a given series, the lowest net rates (and hence highest fluorescence quantum yields) are observed for the "proximal" monometalated complexes **3** and **4** which contain a built-in energy barrier; all other dimers, including heterodimers with zinc in the "distal" position, exhibit relatively fast electron transfer quenching. Secondly, faster overall electron transfer rates are always observed for the 1,3-phenyl bridged "gable" dimers than for the "flat" 1,4-phenyl linked analogues. These two effects appear to be additive. In compound **1**, for instance, where favorable energetic and orientation effects combine, the net rate of electron transfer is exceedingly high.

It is important to realize that throughout the series **1**–**8** the overall electron-transfer process is quite fast. Even for the energetically unfavorable models **3** and **4**, the k_{ET} values are considerably greater than those expected for direct through space (or solvent mediated) electron transfer from H_2P^* to Q.[12a,26,27] This suggests that the "proximal" porphyrin mediates the overall charge separation process. We propose that this could occur by energy migration[14b,28] followed by fast electron transfer,[24] as shown in

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(23) Where fluorescence is observed, the shape of the emission spectrum is always characteristic of the "distal" half of the dimer (see Supplementary Material).

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(25) Subsequent to the submission of this manuscript, transient absorption kinetic studies were carried out and are consistent with this interpretation. For instance, following photoexcitation with an ca. 0.4 ps pulse at 582 nm, compound **1** returns to the ground state with a half-life of roughly 6 ps. For compound **3** two kinetic components were observed with lifetimes of ca. 6 and 85 ps. A full analysis of these data will be presented at a later date.

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eq 1, or via a direct superexchange process.[8,9] Temperature-de-

$$MP_d{}^*\text{–}M'P_p\text{–}Q \xrightleftharpoons{\text{energy migration}} MP_d\text{–}M'P_p{}^*\text{–}Q \xrightarrow{\text{electron transfer}} MP_d\text{–}M'P_p{}^+\text{–}Q^- \quad (1)$$

pendent measurements and studies with analogues of **3** and **4** containing different metals in the "proximal" position (and hence different energy barriers) may allow us to differentiate between these two limiting mechanistic possibilities. Interestingly, much of the controversy regarding the role of the "spectator" chlorophyll in the bacterial photosynthetic reaction center is being framed in just these terms (explicit intermediate versus superexchange);[3-11] our model systems appear to be the first which bear directly on this issue.

Acknowledgment. This work is dedicated to the memory of the late Professor Iwao Tabushi. We thank the Welch Foundation, the Dreyfus Foundation (New Faculty Grant 1984), and the National Science Foundation (PYI Award, 1986) for financial support. We thank Prof. S. Webber for use of his fluorometer and the staff at the Center for Fast Kinetics Research at the University of Texas at Austin (an NIH supported shared user facility) for helping us to record fluorescence lifetimes. J.L.S. also thanks Profs. R. Friesner and T. Mallouk for helpful discussions and critical comments.

Supplementary Material Available: Characterization data for the free-base dimers **5** and **6**, proton NMR spectra for compounds **1**, **3**, and **5** and reference samples, and emission and absorption spectra for compounds **1–12** (8 pages). Ordering information is given on any current masthead page.

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Reinterpretation of the Bicyclomycin–Sodium Methanethiolate Reaction

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Bicyclomycin (**1**) is a clinically useful antibiotic possessing a diverse spectrum of biological activity.[1] In recent years, several chemical hypotheses have been presented to account for the mode of action of this drug.[2-5] Unfortunately, no consensus of mechanism has emerged. In 1979, Iseki and co-workers reported that treatment of **1** with sodium methanethiolate at pH 12.5 led to a 1:1 adduct.[2a] The structure of this compound was assigned as the C(5a)-functionalized sulfide **2** on the basis of the observed ^{1}H NMR and mass spectral data. This finding led to the speculation that sulfhydryl groups present on bacterial inner-membrane proteins irreversibly bind with **1** at the exomethylene group. This result has served as the cornerstone for nearly all current notions concerning the mode of action of bicyclomycin. In this communication, we provide evidence that requires us to reinterpret the proposed structural assignment of the bicyclomycin–sodium methanethiolate adduct **2** and to suggest an alternative mechanism for the chemical activation of bicyclomycin under basic conditions.

Table I. ^{13}C NMR Data for Bicyclomycin Derived Compounds[a]

assignment	**1**	**3**[b]	**4**[c,d]	**2**[e]
C-1	89.46	89.73, 89.81	88.07, 88.21	89.35
C-3	65.50	68.76, 68.81	66.75, 66.95	62.17, 63.36
C-4	36.67	34.21, 34.29	29.86, 30.15[f]	33.18, 34.23
C-5	149.49	48.05	46.52, 46.63	52.10
C-5a	116.95	31.28, 31.37	29.52, 29.73[f]	30.06, 30.65
C-6	82.96	103.40	101.86, 102.01	83.71
C-7	172.52	173.13	169.39, 169.51	172.00[f]
C-9	168.74	175.37	171.84	168.71[f]
C-1′	72.23	80.63	78.85, 78.98	72.62, 72.73
C-2′	78.15	76.88, 76.97	74.77, 74.83	78.03
C-2′-CH_3	24.15	23.41, 23.45	23.56, 23.64	24.20
C-3′	68.42	78.04, 78.09	76.04, 76.14	68.55
other		15.38, 15.66	14.63, 14.72 25.14	15.63, 15.79

[a] The number in each entry is the chemical shift value (δ) observed in ppm relative to Me_4Si. All spectra were obtained at 75.5 MHz. The solvent used was CD_3OD unless otherwise indicated. [b] The NMR spectrum was consistent with the thiolate adducts existing as mixtures of at least two diastereomers present in an approximate 1.4:1 ratio based on comparison of comparable ^{13}C NMR signals. [c] The NMR spectrum was consistent with the thiolate adducts existing as a mixture of at least two diastereomers present in an approximate 1.7:1 ratio. [d] The solvent used was DMSO-d_6. [e] The NMR spectrum was consistent with the thiolate adducts existing as a mixture of two diastereomers present in an approximate 2.1:1 ratio. [f] These peaks may be interchanged.

Treatment of **1** with sodium methanethiolate (1–10 equiv) in aqueous base (pH 12.5) led to the isolation of a semisolid whose ^{1}H NMR spectrum (80 MHz) was virtually identical with the published spectrum of the 1:1 bicyclomycin–methanethiol product[2a] (see Supplementary Material). High resolution mass spectral analysis of the parent ion of this material[6] confirmed the proposed elemental composition ($C_{13}H_{22}N_2O_7S$). Inspection of both the ^{1}H and the ^{13}C NMR spectra indicated that the product mixture consisted of at least two diastereomers. Further analysis of the ^{1}H NMR spectrum (300 MHz) of this adduct revealed several additional features which were in conflict with the originally assigned structure **2**.[7] In particular, the C-3′ diastereotopic protons in the methanethiolate adduct were downfield (~0.26 ppm) from the corresponding protons in bicyclomycin, while the resonance for the C-1′ methine hydrogen was upfield (~0.23 ppm) from the same signal in **1**.[8] The chemical shifts of these protons should not have appreciably changed if the reaction of **1** had occurred exclusively at the exomethylene group in bicyclomycin. Our concerns were amplified upon examination of the ^{13}C NMR spectrum of the methanethiolate adduct (Table I). Comparison of this spectrum with the corresponding spectrum of bicyclomycin[8] showed that large downfield shifts for the C-1′ (8.40 ppm), C-3′ (~9.65 ppm), and C-6 (20.44 ppm) resonances had occurred.[9]

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(7) Compound **3**: ^{1}H NMR (CD_3OD, 300 MHz) δ 1.33 (s, $C_{2'}$–CH_3), 1.75–1.96 (m, C_4*H*H′), 2.07 (s, SCH_3), 2.22–2.35 (m, C_4H*H′*), 2.40–2.56 (m, C_5*H*, C_{5a}*H*H′), 2.80–2.95 (m, C_{5a}H*H′*), 3.83–4.00 (m, $C_{1'}$H, $C_{3'}H_2$, C_3*H*H′), 4.03–4.14 (m, C_3H*H′*).

(8) For a comprehensive study of the NMR spectral properties of bicyclomycin, see: Kohn, H.; Abuzar, S.; Korp, J. D.; Zektzer, A.; Martin, G. E. *J. Heterocycl. Chem.*, in press.

(9) Similar chemical shift values were observed[10] for the triose carbon atoms in the bis-spiro products formed upon treatment of **1** with acid.[11]

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