Photochemistry and Photophysical Properties of Novel, Unsymmetrically Substituted Metallophthalocyanines

David S. Lawrence* and David G. Whitten†

Department of Chemistry, University of Rochester, Rochester, NY, USA

Received 10 June 1996; accepted 14 September 1996

ABSTRACT

A series of novel, unsymmetrically substituted metallophthalocyanines was synthesized, along with their symmetrically substituted analogs, and the effects of structure and metal substitution on their photophysical and photoredox properties were investigated. The macrocycles were synthesized using a mixed-condensation method followed by chromatographic separation of the resulting soluble products. They possess a catechol "active site" and three tert-butyl groups for enhanced solubility. The ground- and excited-state photophysical properties of the free-base, Zn(II) and Pd(II) macrocycles were measured and compared with their symmetrically substituted (tetra[tert-butyl]) analogs. The efficiency with which these macrocycles sensitize the formation of singlet oxygen was determined and discussed in the context of the excitedstate photophysical properties. Several examples of photoinduced electron transfer reactions with one- and twoelectron acceptors are demonstrated and discussed. These soluble molecules can be tuned to optimize their photochemical and redox properties by varying the central metal, axial ligands and other substituents, thereby providing a series of molecules for the investigation of photodynamic therapy and photoinduced electron transfer mechanisms.

INTRODUCTION

Since its serendipitous discovery by Braun and Tchernic in 1907 (1), the phthalocyanine (Pc)[‡] macrocycle has been used in a variety of applications from dyestuffs to chemical sensors. Most of the applications depend upon the physical and photophysical stabilities inherent in the tetraazo-tetrabenz derivative of the porphyrin macrocycle. Phthalocyanines offer advantages over the porphyrins of higher extinction coefficients in the visible region of the spectrum and more resistance to ring degradation, though both have readily tunable redox potentials via changes in the coordinating metal (2). A disadvantage with the unsubstituted Pc is that they are typically insoluble in common solvents and require harsh conditions for their formation. Unsymmetrical functionalization for Pc has been rare until recent years. Through the use of bulky substituents and axial metal ligands, it is possible to overcome these solubility problems. This paper describes the synthesis and characterization of a family of novel, unsymmetrically substituted metallophthalocyanines (MPc), as well as their photochemical and photophysical properties. These macrocycles possess three tert-butyl groups, for solubility, and a catechol group to provide a prospective site for redox chemistry. Their symmetrically substituted counterparts (tetra-[tert-butyl]MPc), also formed in the synthesis, are characterized for comparison (3).

Phthalocyanines and porphyrins have both been used extensively as sensitizers for photoinduced electron transfer reactions (4–6). A simple expression (Eq. 1) relates the free energy of excited-state electron transfer (ΔG^{0*}) based on the ground-state redox potentials, the excitation energy and environmental parameters (7,8)

$$\Delta G^{0*} = 23.06(E^0_D - E^0_A) - \Delta E_{00} - (331.2/\epsilon r_{AD}) \quad (1)$$

where E_{D}^{0} is the oxidation potential of the donor, E_{A}^{0} the reduction potential of the acceptor, ΔE_{00} (in kcal/mol) the energy of the excited state, ϵ the dielectric constant of the solvent and r_{AD} the distance (in Å) between the donor and the acceptor.

Following the synthesis and characterization of the desired, unsymmetrically substituted MPc, several studies were performed to examine the potential for photoinduced electron transfer from the MPc macrocycle to an acceptor molecule. Lever *et al.* have discussed the relevant factors involved in efficient electron transfer between excited-state MPc and acceptors, such as methyl viologen (9). These factors include the quantum yield for formation of the appropriate excited state (singlet or triplet), the lifetime of that excited state, the relative rates of unimolecular back electron transfer (within the solvent cage) *versus* diffusion of the re-

^{*}Current address: Department of Pharmacology, Fox Chase Cancer Center, Philadelphia, PA, USA.

⁺To whom correspondence should be addressed at: Department of Chemistry, 404 Hutchinson Hall, University of Rochester, Rochester, NY 14627, USA. Fax: 716-473-6889; e-mail: whitten@chem.chem.rochester.edu.

[‡]Abbreviations: BP, benzophenone; BSA, bovine serum albumin; CFD, constant fraction discriminator; CV, cyclic voltammetry; DCM, 4-(dicyanomethylene)-2-methyl-6-(4-dimethylaminostyryl)-4H-pyran; DMF, N.N-dimethylformamide; DPV, differential pulse voltammetry; DMSO, dimethylsulfoxide; FAB, fast-atom bombardment; FT, Fourier transform; GC, gas chromatograph; MCA, multichannel analyzer; MCP, multichannel plate; mp, melting point; MPc, metallophthalocyanine; MS, mass spectrum; MW, methylviologen; OD, optical density; Pc, phthalocyanine; PDT, photodynamic therapy; TAC, time-to-amplitude converter; TBAP, tetrabutylammonium perchlorate; THF, tetrahydrofuran; TMS, tetramethylsilane; TPP, tetraphenylporphyrin.

^{© 1996} American Society for Photobiology 0031-8655/96 \$5.00+0.00

action products out of the solvent cage and the relative rate of bimolecular back electron transfer to form the groundstate reactants.

Because nearly all efficient photo-redox reactions that use porphyrins and Pc as sensitizers are initiated from the relatively long-lived triplet state of the macrocycle (10), the triplet properties as well as the excited singlet-state properties of both the symmetrically and unsymmetrically substituted MPc have been investigated. Finally, the photophysical parameters have been used, along with the electrochemical data obtained from cyclic voltammetry measurements, to calculate the thermodynamic driving forces (ΔG^0) involved with photoinduced electron transfer reactions to several one- and two-electron acceptors. The reactivities observed with the various MPc and acceptors are then explained in terms of the above factors.

MATERIALS AND METHODS

All starting reagents were purchased from Aldrich Chemical Co. (Milwaukee, WI) and used as received, unless otherwise noted. Routine UV-visible spectra were obtained on either a Hewlett Packard 8451A or 89531A diode array spectrometer (2 nm resolution). The ¹H-NMR spectra were obtained on a 300 MHz General Electric QE-300 NMR using deuterated solvent locks (99.8%, Cambridge Isotope Laboratories). Chemical shifts are reported in δ units of ppm from tetramethylsilane (TMS). Fourier-transform (FT) IR spectra were measured on a Mattson Galaxy 6020 FT-IR using KBr pellets. Signals are reported in wavenumbers (cm⁻¹). Gas chromatography/ mass spectroscopy (GC/MS) data were obtained on a Hewlett Packard gas chromatograph (model 5890A) coupled to a Hewlett Packard mass selective detector (model 5970). All solvents used in synthesis, purification and characterization were reagent grade or better and were stored over 4 Å molecular sieves. Particular solvent purification procedures are specified when the solvent is used. Melting points (mp) are uncorrected. Fast atom bombardment (FAB)-MS analyses were performed by the Midwest Center for Mass Spectrometry (University of Nebraska-Lincoln) with partial support by the National Science Foundation, Biology Division (grant no. DIR9017262). Elemental analyses were performed by either Galbraith Laboratories, Inc. (Knoxville, TN), Midwest Microlab (Indianapolis, IN) or Desert Analytics (Tucson, AZ). High-resolution UV-visible spectra were obtained on either an IBM Instruments 9430 spectrometer (0.02 nm resolution) or a Perkin Elmer Lambda 19DM UV/Vis/NIR spectrometer (0.05 nm resolution). Fluorescence spectra were measured on a Spex Fluorolog 2 with 1.25 mm slits (bandwidth = 4.71 nm). Phosphorescence spectra were measured on a Spex Fluorolog 2 (bandwidth = 4.25 nm) with a hyperpure germanium detector (North Coast Scientific Corp.) cooled to 77°K.

Synthesis of ortho-(diol)(tert-butyl)₃-PcM

4,5-Dicyano-1,2-methylenedioxybenzene (methylenedioxy-phthalonitrile, 2). 1,2-Methylenedioxybenzene was brominated and then cyanated in a manner similar to that used by Metz *et al.* (11). 4,5-Dibromo-1,2-methylenedioxybenzene (1) was obtained in a 53.1% yield (mp 80–82°C, somewhat lower than the literature value of 86°C (12)). ¹H-NMR (CDCl₃) δ 7.05 (s, 2H, aromatic), 5.99 (s, 2H, – OCH₂O–). Compound **2** was obtained as white needles in a yield of 48.01% (mp 213–215°C). IR 2240 (C=N); ¹H-NMR (CDCl₃) δ 7.13 (s, 2H, aromatic), 6.20 (s, 2H, CH₂); elemental analysis for C9H₄N₂O₂ (172.14 g/mol) calc. C(62.8), H(2.3), N(16.3); found: C(62.38), H(2.3), N(15.98).

Methylenedioxy-(tert-butyl)₃-phthalocyanine $([O \land O][t-Bu]_3$ -PcH₂, **4**). Tert-butyl phthalonitrile (**3**, TCI America, 1.000 g, 5.428 mmol) was combined with **2** (103.8 mg, 0.6031 mmol) in pentanol (25 mL), deaerated with nitrogen and warmed to dissolve the phthalonitriles. Lithium ribbon (416 mg, 59.9 mmol) was added in small pieces and the temperature was raised to reflux (136°C). The reaction was allowed to reflux, under nitrogen, for approximately 2 h. A dark green color was observed to form within minutes of attaining reflux. After cooling to room temperature, glacial acetic acid (25 mL) was added to the mixture. The crude Pc mixture was then evaporated to a dark green sludge. Filtration through a plug of silica ($\sim 5 \times 5$ cm) with toluene gave a mixture of (*t*-Bu)₄PcH₂, (O \land O)₂(*t*-Bu)₂PcH₂ (presumably, *cis*- and *trans*-), and (O \land O)₃(*t*-Bu)PcH₂ by TLC (silica, toluene). The remaining Pc product, (O \land O)₄-PcH₂, did not elute for lack of solubility. The desired AB₃ isomer (**4**) was separated by column chromatography using silica and eluting with a gradient of toluene to 10% EtOAc/toluene giving 178 mg (0.225 mmol, 14.9%—based on starting phthalonitrile). UV-visible (benzene—1.16 μ M) 347 nm (log $\epsilon = 4.88$), 440 (sh, 4.11), 596 (4.48), 642 (sh, 4.79), 659 (5.16), 697 (5.25); IR 1047 (C-O-C stretch); 'H-NMR (benzene-d₆) δ 9.40–6.85 (m, 11H, phenyl), 5.53 (s, 2H, $-OCH_2O-$), 1.71 (m, 27H, *t*-butyl), -4.68 to -4.84 (bs, 2H, pyrrole-NH); FAB-MS: m/z = 727.3 (M+H)^+.

Methylenedioxy-tri(tert-butyl)-phthalocyanatozinc(II) $([O \land O](t-Bu]_3-PcZn, 4-Zn)$. The reaction was run in the same manner as for the free-base compound except for the addition of anhydrous zinc acetate (299 mg, 1.63 mmol) to the mixture. Purification was analogous to the free-base compound (4) except that initial filtration through silica used diethyl ether (instead of toluene) and the separation of the isomers was done using a gradient of CHCl₃ to CHCl₃/Et₂O (1:1). The desired AB₃ isomer was obtained as 239 mg (0.302 mmol, 20.1%—based on starting phthalonitrile) of a dark green film. Metallation of the free-base compound, 4, with Zn(OAc)₂ also gave the same product. UV-visible (benzene-2.11 μ M) 352 nm (log $\epsilon = 5.02$), 443 (sh, 3.87), 609 (4.76), 648 (sh, 4.78), 675 (5.58); IR 1047 (C-O-C stretch); 'H-NMR (benzene-d₆) δ 9.25–6.80 (m, 11H, phenyl), 5.65 (s, 2H, -OCH2O-), 1.65 (m, 27H, t-butyl); FAB-MS: m/z = 789.2 (M+H)⁺.

Methylenedioxy-tri(tert-butyl)-phthalocyanatopalladium(II) $([O \land O][t-Bu]_3$ -PcPd, 4-Pd). 4 (117 mg, 0.161 mmol) was metallated with anhydrous palladium(II) acetate (43 mg, 0.193 mmol) in refluxing N,N-dimethylformamide (DMF) (~153°C). The reaction was monitored by UV-visible spectroscopy (in toluene) following the formation of a single Q-band at 660 nm (from the split Q-bands at ~660 and 700 nm). After ~4.5 h, the reaction was complete and allowed to cool to room temperature. The DMF was removed by extraction of the benzene-diluted mixture with 10% HCl (aq.) followed by washing with brine and drying with MgSO₄. The crude product was chromatographed on silica with an elution gradient of toluene to 10% EtOAc/toluene giving (after vacuum desiccation at 60°C overnight) 73 mg (0.088 mmol, 54.5%). UV-visible (benzene—2.93 μ M) 336 nm (log ϵ = 4.72), 360 (sh, 4.58), 594 (4.61), 634 (4.78), 658 (5.33); fluorescence (benzene-2.93 µM, excitation @ 593 nm) 690 nm; IR 1047 (C-O-C stretch); ¹H-NMR (benzened₆) δ 8.45-6.85 (m, 11H, phenyl), 5.35 (s, 2H, -OCH2O-), 1.55 (m, 27H, t-butyl); FAB-MS: $m/z = 830.2 (M^{+})$.

(Tert-*butyl*)₄-*phthalocyanine* ($[t-Bu]_4$ -*PcH*₂). The first fraction from the mixed condensation reaction above was separated and rechromatographed (silica, toluene) to give a pure product. The ¹H-NMR and electronic spectra agreed with published data (13). Molecular weight was confirmed by FAB-MS: m/z = 738.4 (M⁺).

(Tert-butyl)₄-phthalocyanatozinc(II) ($[t-Bu]_4$ -PcZn). The zinc chelate was obtained in a manner analogous to the free-base compound. Metallation of $(t-Bu)_4$ -PcH₂ with Zn(OAc)₂—as above—also produced the desired compound. ¹H-NMR and electronic spectra agreed with published data (14). Molecular weight was confirmed by FAB-MS: m/z = 801.2 ($[M+H]^+$).

(Tert-butyl)₄-phthalocyanatopalladium(II) ([t-Bu]₄-PcPd). The free-base (t-Bu)₄-PcH₂ was metallated with either Pd(OAc)₂—as above—or *trans*-Pd(C₆H₅CN)₂Cl₂ (formed from PdCl₂ heated in benzonitrile (100°C) and recrystallized from benzene (15)). The ¹H-NMR and electronic spectra agreed with published data (13). Molecular weight was confirmed by FAB-MS: m/z = 843.2 ([M+H]⁺).

Dihydroxy-(tert-butyl)₃-phthalocyanine ($[diol][t-Bu]_3-PcH_2$, 5). Compound 4 (50 mg, 0.069 mmol) was deprotected with BCl₃ (414 μ L, 0.414 mmol, 1.0 *M* in CH₂Cl₂) at room temperature in CH₂Cl₂. Reaction aliquots were removed, quenched with methanol and analyzed for product formation by TLC (silica, 1% EtOAc/toluene). A second aliquot of BCl₃ (414 μ L, 1.0 *M* in CH₂Cl₂) was added after 5 h. After approximately 22.5 h, the reaction was quenched by the addition of 10 mL methanol and the solvent removed *in vacuo*. Flash chromatography (silica, 5% EtOAc/toluene—to remove unreacted

Table 1. Half-wave potentials for MPc (in CH_2Cl_2)

- Compound	Potentials (V vs SCE)						
	MPc (-3)/ MPc (-4)	MPc(-2)/ MPc(-3)	MPc(-1)/ MPc(-2)	MPc(0)/ MPc(-1)	MPc(1)/ MPc(0)		
$(\text{Diol})(+)_3$ -PcH ₂	-1.37	-0.919	+0.381	+0.881	+1.26		
$(Diol)(+)_3$ -PcZn	_	-0.391	+0.369	_	+1.33		
$(Diol)(+)_3$ -PcPd	-1.45	-1.03	+0.369		+1.31		
$(+)_4$ -PcH ₂	-1.25	-0.946	+0.376	+0.860	+1.29		
$(+)_4$ -PcZn	-1.28	-0.928	+0.396		+1.18		
(+) ₄ -PcPd	-1.43	-1.04	+0.411	+1.06	+1.45		

4—and then 1% HOAc/THF to elute the product) gave, after rotary evaporation of the solvent and vacuum desiccation overnight (60°C), 39 mg of a dark green film (0.055 mmol, 80%). UV–visible (8.5 m*M* in benzene) 346 nm (log ϵ = 4.35), 601 (3.93), 644 (4.13), 662 (4.46), 698 (4.51); fluorescence (benzene, excitation at 601 nm) 702, 736, 781 nm; IR ~3500 (OH stretch); ¹H-NMR (DMSO-d₆) & 9.15 (bs, 2H, ϕ OH), 8.25 (bs, 2H, ϕ H-catechol), 7.8 (m, 9H, aromatic), 1.35 (s, 27H, *t*-butyl). The phenolic peaks were confirmed by exchange with D₂O. ¹³C-NMR (CDCl₃) & 152.1 (phenolic carbons), 136.4, 128.3, 126.1 (aromatic), 34.3, 31.7, 30.9, 21.7 (*tert*-butyl); high-resolution FAB-MS: m/z = 714.3416 (M⁺), calculated composition—C₄₄H₄, N₈O₂ (-2.0 ppm deviation).

Dihydroxy-(tert-butyl)₃-phthalocyanatozinc(II) ([diol][t-Bu]₃-PcZn, 5-Zn). Deprotection was performed in the same manner as for the free-base compound, 5. The NMR and FT-IR data were equivalent. UV-visible (22 μ M in benzene) 351 nm (log ϵ = 3.98), 610 (3.60), 645 (sh, 3.65), 677 (4.31); fluorescence (benzene, excitation at 610 nm) 684, 710 (sh), 753 nm; high-resolution FAB-MS: m/z = 777.2646 (M+H)⁺, calculated composition—C₄₄H₄₁N₈O₂Zn (0.3 ppm deviation).

Dihydroxy-(tert-butyl)₃-phthalocyanatopalladium(II) ([diol][t-Bu]₃-PcPd, **5-Pd**). Deprotection was performed in the same manner as for the free-base compound, **5**. The NMR and FT-IR data were equivalent. UV-visible (12 μ M in benzene) 334 nm (log $\epsilon = 4.10$), 598 (3.86), 636 (sh, 3.94), 660 (4.30); fluorescence (benzene, excitation at 598 nm) 702, 735, 782 nm; high-resolution FAB-MS: m/z = 816.2291 (M⁻⁻), calculated composition—C₄₄H₄₀N₈O₂¹⁰⁴Pd (-2.4 ppm deviation).

Cyclic voltammetry

Oxidation potentials (Table 1) were measured on an Electrochemical Analyzer model BAS 100B (Bioanalytical Systems, West Lafayette, IN) using the standard three-electrode configuration for cyclic voltammetry (working: Pt disk, reference: Ag/AgNO₃ [in CH₃CN with 0.1 *M* tetrabutylammonium perchlorate (TBAP)], counter: Pt wire). Measurements were done in dry, freshly distilled solvents using TBAP (0.1 *M*) as the electrolyte, which was recrystallized from absolute ethanol and vacuum desiccated at 100°C overnight before use. Samples were deaerated with nitrogen before and between measurements. Half-wave potentials (E_{1/2}) were obtained using a combination of cyclic voltammetry (CV) and differential pulse voltammetry (DPV) methods. The E_{1/2} values from the CV curves were calculated from (E_{0x} + E_{red})/2, whereas those from the DPV were obtained directly from the peak values.

In order to compare the potentials obtained in a nonaqueous environment to those obtained by other workers in a variety of solvent systems and measurement conditions, the ferrocenium/ferrocene (Fc'/Fc) couple was used as an internal standard (Fc'/Fc couple vs SCE (saturated calomel electrode): 0.45 V in CH₂Cl₂ (16–18)).

Photophysical measurements

Measurements of fluorescence quantum yields (Φ_F). Dilute solutions of each Pc (10–30 μ M) were absorbance matched at the excitation wavelength to a dilute solution of (*t*-butyl)₄-PcH₂ (A_{624 nm} = 0.055

 \pm 0.001, in CHCl₃). Absorbances were kept low and the emission scan was done using a front-face geometry to minimize any errors due to aggregation and self-absorbance. The relative fluorescence quantum yields (Φ_F) were calculated by the following equation:

$$\Phi_{\text{F(sample)}} = \frac{A_{(\text{sample})}}{A_{(\text{std.})}} \times \Phi_{\text{F(std.)}}$$
(2)

where A represents the area of the fluorescence emission envelope and Φ_F the fluorescence quantum yield of the (*t*-butyl)₄-PcH₂ standard (0.77) (19). Emission spectra were not corrected for variations in the excitation lamp output.

Measurement of fluorescence lifetimes (τ_F). Time-correlated single photon counting experiments were carried out using a modelocked Nd:YLF laser (Quantronix) operating at 76 MHz as the primary laser source. The second harmonic (KTP crystal) of the Nd: YLF laser was used to synchronously pump a dye laser (Coherent 700) circulating rhodamine 6G in ethylene glycol as the laser medium. The pulsewidth of the dye laser was typically 8 ps, as determined by autocorrelation, and was cavity dumped at a rate of 1.9 MHz. The dye laser was tuned to the desired wavelength for sample excitation. Emission from the sample was collected by two convex lenses and focused at the entrance slit of a Spex 1681 monochromator (0.22 m) and was detected by a red-sensitive multichannel plate (MCP) detector (Hamamatsu R3809V-01). The single-photon pulses from the MCP detector were amplified and used as the stop signal for a time-to-amplitude converter (TAC, EG&G Ortec) while the signal from a photodiode, detecting a small fraction of the dye laser output, was used as the start signal for the TAC. The start and stop signals for the TAC were conditioned before entering the TAC by passing through two separate channels of a constant fraction discriminator (CFD, Tennelec). The output of the TAC was connected to a multichannel analyzer (MCA) interface board (Norland 5000) installed inside a 486DX2 personal computer. The MCA was controlled by software from Edinburgh Instruments (Edinburgh, UK). The same software was used to carry out the deconvolution of the data and exponential fitting using the nonlinear least-squares method.

Measurement of singlet oxygen quantum yields (Φ_3). Time-resolved measurements of ${}^{1}O_2$ luminescence were made using a germanium photodiode, as described by Rodgers and Snowdon (20). Solutions of the chromophores were made in benzene-d₆ with a low optical density at the exciting wavelength. The tetraphenylporphyrin (TPPH₂) reference solution (in benzene) was made to match the optical density (OD) of the sample solutions at the excitation wavelength of each. The unsymmetrically substituted Pc samples, (diol)(*t*-butyl)₃-PcM, were excited at 570, 580 and 600 nm, for M = H₂, Zn and Pd, respectively. The symmetrically substituted Pc (*t*-butyl)₄-PcM were excited at the same wavelength was their unsymmetrical counterparts. For PdTPP, the excitation wavelength was 435 nm. The TPPH₂ has a Φ_{Δ} value of 0.58 in benzene (21). The slopes were calculated from lines with a linear correlation of 0.995 or better. As a control, nitrogensaturated samples did not produce any signal at 1270 nm.

The Φ_{λ} values were also determined by the IR luminescence technique using perinaphthenone (phenalenone, Aldrich) as a reference (22). When excited at 337 nm, perinaphthenone sensitizes the formation of ${}^{1}O_{2}$ with a quantum yield of 0.98 \pm 0.15 in CHCl₃. Relative quantum yields were measured in the same manner as the fluorescence quantum yields by comparing the area under the emission envelope for ¹O₂ (centered at 1270 nm). Solutions of the Pc and porphyrins were absorbance-matched in CHCl₃ ($A_{337} = 0.140$ \pm 0.003) to a solution of perinaphthenone (in CHCl₃). All solutions were air equilibrated. Emission from 'O2 was measured with the same instrumentation used for phosphorescence measurements. A cut-off filter (780 nm) was used to remove the second-order scattering from the Pc (or porphyrin) fluorescence emission. The assignment of the 1270 nm emission to 'O2 was confirmed by deaerating the sample with nitrogen. Under this condition, no 1270 nm emission was observed.

Triplet-triplet absorption spectra and lifetimes (τ_T). Time-resolved triplet-triplet absorption spectra and lifetimes were measured by nanosecond laser flash photolysis on freeze-pump-thaw degassed solutions (three cycles, ~3 µTorr) in either 2-methyl-tetrahydrofuran (MeTHF), or Et₂O/methylcyclohexane (3:2) for (*t*-butyl)₄-PcH₂ and (*t*-butyl)₄-PcPd. These solutions were the same as those used for the phosphorescence measurements ([MPc] = 10-30 µM).

Table 2.	Fluorescence and	phosphorescence	of MPc lowest	lying singlet an	d triplet states*
----------	------------------	-----------------	---------------	------------------	-------------------

Compound	λ _F (nm)	$\Phi_{\rm F}$	τ _F (ns)	λ _P (nm)	λ ₁ (nm)	τ _T (μs)	$\Delta \epsilon_{\mathrm{T}}$	Φ_{T}	Conditions
PcH ₂	700	0.7	0.28†	_	480	125	1.8×10^{4}	0.17±	77°K. Cl-naphthalene
(t-Butyl) ₄ PcH ₂	708	0.77	9.00	_	490	83.0	4.5×10^{4}	0.10	298°K, benzene
$(HO)_{2}(+)_{3}PcH_{2}$	706	0.30	7.22	_	500	67.0	4.8×10^{4}	0.060	298°K, benzene
PcZn	683	_	_		480	125	1.6×10^{4}	0.65‡	300°K, Cl-naphthalene
PcZn		0.3	100	1093	_	_	_		77°K, Cl-naphthalene
(t-Butyl)₄PcZn	686	0.37	3.63	1100§	510	41.1	4.9×10^{4}	0.24	298°K, benzene
$(HO)_2(+)_3PcZn$	685	0.18	3.35	1110§	500	176	5.3 × 10 ⁴	0.038	298°K, benzene
PcPd	664	_		1007	_	_	—		300°K. Cl-naphthalene
PcPd		5×10^4	10	990	_		_		77°K
(t-Butyl) ₄ PcPd	670	0.048	0.024	1028	520	10.4	5.5×10^{4}	0.49	298°K, benzene
$(HO)_2(+)_3PcPd$	703	0.069	5.30	1036§	520	8.30	3.0×10^{4}	0.23	298°K, benzene

*Ferrandi (42).

‡Fuke et al. (66).

§Measured in MeTHF at 298°K (77°K for M = Zn).

†In N,N-DMF/H₂O (9:1).

Measured in Et₂O/methylcyclohexane (2:3) at 298°K.

The instrumentation is essentially the same as that used by others (23,24), except that the excitation energy was provided by the same excimer/dye laser system which was used for the ${}^{1}O_{2}$ measurements (600 nm, except for the Pd complexes at 590 nm). The timescale was 10 µs and the maximum laser beam energy was typically 3–15 mJ/cm². Measurements were made at ambient temperatures (23 ± 2°C) and data points were the average of eight replicate shots taken at 10 nm intervals. Optical density values in the spectra were taken from the average intensity values obtained in the first 4 µs after the excitation pulse. Lifetime values were obtained from kinetic analysis at both the maximum triplet-triplet absorbance and maximum bleaching wavelengths (using the linear least-squares fitting algorithm, Dr. Ian Gould). The Δ OD values plotted in the spectra represent the difference in absorbance of the excited triplet state (T₁ \leftarrow T_n) and the ground state (S₀ \leftarrow S_n). These values result from

$$\Delta OD = (\epsilon_{\rm T} - \epsilon_{\rm g})C_{\rm o}l \tag{3}$$

where ϵ_T and ϵ_g represent the triplet- and ground-state extinction coefficients, respectively, C_o the initial concentration of ground states and I the path length of the cell.

Determination of triplet-triplet extinction coefficients ($\Delta \epsilon_T$). The extinction coefficient of the MPc triplet-triplet absorbance ($\Delta \epsilon_T$) was determined by the relative method of Carmichael and Hug (25,26). The same laser flash photolysis setup used above for the triplettriplet absorbance measurements was used, except that the excitation wavelength was changed to 660 nm so that lower concentrations of the Pc could be used. The 660 nm excitation energy was generated by a DCM (4-[dicyanomethylene]-2-methyl-6-[4-dimethylaminostyryl]-4H-pyran, Exciton) solution in dimethyl sulfoxide (DMSO). Unattenuated excitation energies were 21-30 mJ/cm². Beta-carotene solutions (Aldrich, 0.1 mM) were made fresh before each measurement in dry benzene and deaerated with nitrogen. Phthalocyanine concentrations were adjusted such that the absorbance at the exciting wavelength (660 nm) was approximately 0.2 (~10 μ M). The signals used for calculations were the average of 8-20 shots, as necessary to achieve a sufficiently noise-free signal. Knowing the lifetime of the Pc triplet (measured above) and assuming that the quenching rate constant of β -carotene for the Pc triplet (k_{α}) is at or near the diffusion-controlled limit (27), the fraction of Pc triplets that are quenched by a given concentration of β -carotene ([O]) can be calculated with the following relationship,

$$k_{q}[Q]/(k_{q}[Q] + k_{0})$$
 (4)

where k_0 (triplet decay rate in the absence of quencher) is the inverse of the triplet lifetime (τ_T). This shows that greater than 90% of the Pc triplets (with τ_T greater than 10 µs) are quenched by a β -carotene concentration of 0.1 mM. Therefore, we can assume that the rate of formation and decay of the β -carotene triplet is directly related to the formation and decay of the Pc triplet.

The amount of β -carotene triplet present immediately after the

excitation pulse (at time = 0) is determined by fitting the exponential decay from a long timescale plot and extrapolating to the top of the excitation pulse (at time = 0). Likewise, the amount of ³PcM present immediately after the excitation pulse (at time = 0) is determined by fitting the exponential growth of the β -carotene signal from a short timescale plot and extrapolating to the value at time equals zero. Assuming that the two triplet concentrations are equal (*i.e.* for every ³PcM that is formed, one ³[β -carotene] is formed), then

$$OD_{Pc}/\epsilon_{Pc} = OD_{C}/\epsilon_{C}$$
 (5)

by the Beer–Lambert Law (28) (where Pc represents the Pc triplet and C represents the β -carotene triplet). Using the literature value for $\epsilon_C (\Delta \epsilon_T (515 \text{ nm}) = 187000 \pm 53500 M^{-1} \text{ cm}^{-1} (25))$, the values of $\epsilon_{Pc} (515 \text{ nm})$ can be calculated from the triplet–triplet absorption spectrum for each MPc. The values listed in Table 2 represent the average of at least three measurements at different excitation beam energies where the signal obtained is linear with the excitation energy. The standard deviations from the mean were between 3 and 17%.

Measurement of the quantum yield of triplet formation (Φ_T). The same nanosecond laser flash photolysis setup that was used for measurement of the triplet-triplet absorption spectra was used to measure the relative quantum yields of triplet formation (Φ_T). Because the benzophenone triplet ($\Phi_T \Delta \epsilon_T = 7220 \pm 320 \ M^{-1} \ cm^{-1}$ at 530 nm (29)) was used as the reference compound, excitation was provided by the excimer-pumped DMQ (Exciton) dye, in p-dioxane, at 360 nm. The benzophenone (BP) was recrystallized and sublimed before use. Both the BP standard and the Pc sample solutions were made in dry benzene, at sufficiently low concentrations (OD₃₆₀ = 0.255 ± 0.005) to minimize inner filtering and maintain a uniform excitation energy flux (29). The initial excitation energy was measured, as above, to be 21-24 mJ/cm². In a manner similar to that used for the time-resolved singlet oxygen quantum yields, the initial excitation energy was attenuated with neutral density filters to obtain a linear fit with the resulting triplet ΔOD value. Attenuated excitation energies of 0.32-2.9 mJ/cm² gave such a linear response. The filters were calibrated using the transmittance at 360 nm. Triplet absorbance values (averaged over 30 shots) were measured at the λ_{max} of each Pc using excitation energies that were linear with the absorbance value obtained.

Photooxidation of Pc

Steady-state irradiation with light of wavelength above 600 nm was produced by a 250 W xenon lamp fitted with a Corning filter (#2-63) and a water-filled filter (for IR). Carbon tetrabromide (Aldrich) was recrystallized from ethanol and dried in a vacuum desiccator overnight. Carbon tetrachloride (Aldrich) was used as received. The methylene chloride was freshly distilled from K_2CO_3 and stored over molecular sieves until used. The Cr(urea)₆Cl₃ used for actinometry



Figure 1. Synthesis of AB_3 -type MPc. Reaction schemes show the formation of methylenedioxy-phthalonitrile (2), which, with the commercially available 4-*t*-butyl-phthalonitrile (3), are converted into their respective diiminoisoindoline intermediates and then combined in a 1:9 ratio to form the dilithium Pc, which are either protonated with acetic acid (as shown) or metallated as described in the Materials and Methods to give the desired macrocycles (4).

with $h\nu > 600$ nm was produced from the aqueous reaction of CrCl₃·6H₂O and urea with HCl catalysis, according to the method of Brauer (30). The reaction was carried out under dim red light and vacuum desiccated overnight in the dark at 60°C.

RESULTS

Synthesis

Although symmetrically substituted Pc may be made by simply tetramerizing substituted phthalonitriles (or their diiminoisoindoline derivatives), the mono- (or unsymmetrically) substituted macrocycles pose a more difficult problem. Several methods have been exploited for creating monosubstituted Pc including mixed condensation, polymer-supported synthesis and ring expansion of a subphthalocyanine. The 1: 9 ratio improved this situation immensely (Fig. 1). Using a simple statistical model, McKeown et al. demonstrated that, by combining the starting materials in a 1:9 ratio, one can obtain significantly less of the undesired A₂B₂- and A₃B-type macrocycles while losing only a small amount of the desired AB_3 -type product (31). The 1:3 ratio of starting materials was examined with this system but gave a mixture of products that were inseparable by chromatographic means. In the case of the (diol)(t-Bu)₃-PcM synthesized here, solubility was imparted by the *tert*-butyl moieties providing not only steric bulk but also the robust nature of the alkyl group toward further reactions. The intermediate diiminoisoindolines shown in Fig. 1 were not isolated as in other published syntheses (32,33) but were directly cyclized to the macrocycle. Replacing the single tert-butyl group of our macrocycle with two n-butyl groups was investigated in order to alleviate the

problem of positional isomerization. Unfortunately, extensive interfacial stacking limited the solubility necessary for effective chromatographic separation. Other researchers have reconciled this positional isomerization problem by using such substituents as PhOCH₂-, functionalization of phthalamide or phthalic anhydride substituents, or by using *para*-substituted phthalonitriles.

The polymer-supported route has been used successfully by several researchers (33-35), but suffers the disadvantage of low polymer-loading limits that results in small yields of product. By far, the most elegant method for creating AB₃type Pc utilizes the subphthalocyanine as an intermediate (36-38). The subsequent ring-expansion reaction leads to one and only one Pc product. The only purification necessary is the removal of unreacted starting materials and other nonmacrocyclic (and, therefore, not highly colored) side products. Kobayashi demonstrated the usefulness of this method by creating a series of AB₃-type Pc with increasing annulation of the A moiety and a concurrent increase in the λ_{max} of the absorbance spectrum. However, Weitemeyer et al. have recently shown by HPLC and DCI-MS that the ring enlargement reaction may actually lead to more than one Pc product (39). It is evident that more investigation is needed to explore the breadth of this synthetic method as it may be applied to other synthetic problems, as well as the optimization of the yields and purification methods.

CV

The oxidation and reduction potentials measured for the three A_4 and three AB_3 MPc are tabulated above (Table 1). The assignments shown are tentatively made by comparison with previously published values for the $(t-butyl)_4$ -MPc (40). Because the origins of these potentials are less than clear, no attempt will be made to assign them definitively to either macrocyclic ring or metal oxidation/reduction. However, for nonelectroactive central metals, the redox process is generally believed to involve the macrocyclic ring rather than the central metal (40). As the first oxidation potentials for the (t-butyl)₄-PcM compounds roughly correspond to those for the $(diol)(t-butyl)_3$ -PcM, it is assumed that the observed redox couples are from the ring oxidation process (Pc[-1])/Pc[-2]) and not from the catechol/o-quinone couple. The catechol/o-quinone couple is commonly observed at potentials near 0 V (vs SCE) (41). Although Pc with the catechol/ o-quinone moiety have not been previously observed, similar aromatic, heterocyclic catechol/o-quinone couples have been studied electrochemically. The solvents and pH of the MPc electrochemical experiments most likely precluded observation of the desired redox couple.

Photophysical measurements

Fluorescence quantum yields (Φ_F) and lifetimes (τ_F) . The relative quantum yields of fluorescence emission for the three symmetrically substituted (t-butyl)₄-PcM and the three unsymmetrically substituted (diol)(t-butyl)₃-PcM are shown in Table 2 along with the fluorescence lifetimes. The literature values of the analogous unsubstituted MPc are shown for comparison (42). The position of the emission band (assigned to the 0,0 transition) is relatively consistent within the particular groups of the same central substituent. The notable exception to this occurs with the palladium-substituted Pc. The values of the Φ_F vary as expected (decreasing from $M = H_2$ to Zn to Pd), as more of the excitation energy decays through intersystem crossing to the triplet manifold. This is the result of increased spin-orbit coupling between the central metal substituent and the macrocyclic π -electrons (43). Deaeration of the sample solutions was found to be unnecessary as the fluorescence intensities from purged (with argon for 15 min), freeze-pump-thaw degassed and unpurged solutions varied by no more than 1-2%. This is most likely because the fluorescence lifetimes are too short for quenching by the amount of oxygen present in air-equilibrated solutions (1.91 mM) (44) to affect the emission intensity by an amount greater than the inherent accuracy of the fluorometer. Using the relationship in Eq. 4 below, and assuming that ³O₂ quenches the excited singlet state at a diffusion-controlled rate ($\sim 10^{10} \text{ s}^{-1}$), an oxygen concentration of 10 mM (essentially saturated (44)) will quench 47% of the excited singlet states of (t-butyl)₄-PcH₂ (the longestlived singlet— $\tau_F = 9.00$ ns). However, comparison of the fluorescence intensity changes for benzene solutions of all six MPc showed a variety of quenching behaviors for argonsaturated versus oxygen-saturated solutions. As expected, the percentage of fluorescence quenching paralleled the fluorescence lifetimes ($\tau_{\rm F}$). Using the relationship in Eq. 7 below an average quenching rate constant (k_o) value of 2.94 \times $10^9 M^{-1} s^{-1}$ was obtained. Nevertheless, it has been suggested that ³O₂ enhances the rate of intersystem crossing, thus lowering the observed quantum yield of fluorescence (45). The values of $\Phi_{\rm F}$ tabulated in Table 2 are expected to be accurate because all were measured against (t-butyl)₄-PcH₂ under identical conditions of air equilibration.

Triplet-triplet absorption difference spectra and lifetimes. Spectral peak values (λ_T) and lifetimes (τ_T) are shown in Table 2 for the six symmetrically and unsymmetrically substituted MPc. The difference spectra for the six MPc agreed well with literature examples for both the maximum triplettriplet absorbance $(T_1 \leftarrow T_n)$ and ground-state bleaching processes $(S_n \leftarrow S_n)$.

The tabulated triplet lifetimes (τ_T) represent a lower limit due to the presence of a small amount of oxygen that will be present unless the solution is perfectly deaerated. Further quenching of the excited triplet state (³Pc) may be due to triplet-triplet annihilation given the high Pc concentrations necessary to obtain sufficient signal strength with 590 nm excitation. Nevertheless, the values obtained for the six MPc fall within the 10–200 µs range reported for other MPc triplet states (24,27).

Determination of triplet-triplet extinction coefficients $(\Delta \epsilon_T)$. The well-known triplet quencher, trans- β -carotene, was used to quench the Pc triplet states formed by the laser excitation pulse (46,47). The β -carotene triplet is formed only by energy transfer from another excited triplet and cannot be formed by direct excitation due to its very low intersystem crossing efficiency (~0) (27). Therefore, formation of the β -carotene triplet is not only useful for calculation of $\Delta \epsilon_T$, but also for confirmation of the sensitizer (MPc) triplet itself.

Measurement of the quantum yields of triplet formation (Φ_T) . The quantum yields of triplet formation were determined using the "comparative method" espoused by many

Table 3. Singlet oxygen quantum yields

Compound	$k_{\rm o} (M^{-1} {\rm s}^{-1})$	Φ _Δ TR	$\Phi_{\Delta}SS$	
(t-Butyl) ₄ -PcH ₂	1.52×10^{9}	0.22	0.20	
(t-Butyl) ₄ -PcZn	1.50×10^{9}	0.34	0.25	
(t-Butyl) ₄ -PcPd	2.39×10^{9}	0.54	0.52	
$(Diol)(t-Butyl)_2-PcH_2$	1.44×10^{9}	0.14	0.14	
$(Diol)(t-Butyl)_2-PcZn$	1.01×10^{9}	0.39	0.23	
$(Diol)(t-Butyl)_2-PcPd$	2.16×10^{9}	0.49	0.36	
H_TPP		0.58*	0.32	
ZnTPP	_	0.73*	0.72	
PdTPP	—	0.88	0.78	

*Rossbroich et al. (21).

workers (29,48-51). This method requires the extinction coefficients measured above, as well as the extinction coefficient and quantum yield $(\Delta \epsilon_T \Phi_T)$ of a reference compound (BP). With the solutions of both BP and the MPc sample matched in terms of ground-state absorbance at the excitation wavelength, the amount of excitation energy absorbed by each compound will be equivalent. Assuming constant excitation energy from the pulsed dye laser (checked periodically as described in the Materials and Methods), the ratio of the concentrations of triplet formed by each compound is related to the quantum yield of triplet formation for each compound. The concentrations are determined by measuring the ΔOD at the λ_{max} of each compound (extrapolated from the first-order decay as above) and dividing by the appropriate extinction coefficient (following the Beer-Lambert Law). The ratios of the triplet concentrations of the MPc sample and the BP standard, multiplied by the quantum yield for BP (1.0) gives the Φ_{T} values for the MPc. The values at each excitation energy are then extrapolated to a theoretical excitation energy of zero to obtain the quantum yield values reported in Table 2. Linear regression gave lines with correlation coefficients of 95% or greater. Errors in measurement are estimated to be approximately 10%. The use of low ground-state concentrations and low excitation energies to determine Φ_{T} minimizes the four complicating factors enumerated by Hurley et al. (29): (a) ground-state depletion by the excitation pulse, (b) "inner filtering," (c) cycling of absorbed energy and (d) excitation intensity gradients.

Singlet oxygen quantum yields (Φ_{Λ}). As described in the Materials and Methods section, the quantum yields for the formation of ¹O₂ were measured using both time-resolved and steady-state luminescence techniques. The former used TPPH₂ ($\Phi_{\Delta} = 0.58$) (21) as a standard in benzene. The deuterated solvent used for the samples is necessary in order to achieve a long enough singlet oxygen lifetime for effective detection at low signal intensities ($\tau_{A} = 30 \ \mu s$ [benzene], τ_{A} = 600 μ s [benzene-d₆]) (52). The latter technique used perinaphthenone as a standard in chloroform. Again, the solvent was chosen to enhance the lifetime of the ${}^{1}O_{2}$ ($\tau_{\Delta} = 240$ -300 μ s) (52). The results are shown in Table 3 for the three symmetrically and three unsymmetrically substituted MPc as well as free-base zinc and palladium TPP. The table compares the rate constants of ³PcM quenching by ground-state ${}^{3}O_{2}$ (k_{q}) with the quantum yields for ${}^{1}O_{2}$ formation using both time-resolved ($\Phi_{\Delta}TR$) and steady-state ($\Phi_{\Delta}SS$) techniques.



Figure 2. Phosphorescence of $(diol)(t-butyl)_3$ -PcPd and emission spectra of singlet oxygen formed by sensitization with $(diol)(t-butyl)_3$ -PcPd. Spectra were measured as described in the Materials and Methods.

All of the solutions were presumed to be equilibrated with ambient oxygen concentrations (1.91 mM at 25°C and 760 mm Hg (44)). The spectra shown in Fig. 2 illustrate the process of singlet oxygen formation by showing the phosphorescence obtained at 1036 nm with a deaerated solution of (diol)(*t*-Bu)₃-PcPd (in benzene-d₆) *versus* the ¹O₂-emission obtained at 1270 nm with an air-equilibrated solution of (diol)(*t*-Bu)₃-PcPd (in benzene-d₆). Note the absence of any phosphorescence signal in the presence of air. The "heavy atom effect" (53) is observed with each of the macrocycle series (Φ_{Δ} [M = H₂] $< \Phi_{\Delta}$ [M = Zn] $< \Phi_{\Delta}$ [M = Pd]), confirming the enhancement of triplet formation with central substituents of increasing molecular weight.

The value obtained with the time-resolved method for $(diol)(t-Bu)_3$ -PcPd ($\Phi_{\Delta} = 0.49$) may be inaccurate due to the low energy at which the ${}^{1}O_{2}$ signal was linear with laser energy (1-3% of the incident energy). This low excitation energy produced a very low-intensity signal that was difficult to fit accurately. The fact that only three data points were obtained in the linear region (of emission versus excitation energy) made the calculation of the slope somewhat tenuous.

The Φ_{Δ} value obtained with the steady-state method for $(t-Bu)_4$ -PcZn ($\Phi_{\Delta} = 0.25$) may be low due to a possible photochemical reaction of the Pc with the solvent. A photolysis measurement, made subsequent to the quantum yield measurements, showed bleaching of the $(t-Bu)_4$ -PcZn absorbance bands upon irradiation with wavelengths of light greater than 600 nm. Although no change in the absorption spectrum of $(t-Bu)_4$ -PcZn was observed after the quantum yield determination, it is possible that the chloroform acted to quench the Pc fluorescence and artificially reduced the value of Φ_{Δ} . This bleaching behavior was not observed with any of the other compounds.

The rate constants of triplet quenching by ${}^{3}O_{2}$ shown in Table 3 were determined using Eq. 10 below. The triplet lifetimes (τ_{T}) were measured in benzene, saturated with nitrogen or oxygen, at the maximum absorbance wavelength (λ_{T} from Table 2). All six values obtained are reasonably close to the spin-statistical diffusion-controlled limit for the quenching of a triplet excited-state molecule by triplet ground-state oxygen ($1.11 \times 10^{9} M^{-1} s^{-1}$ in benzene (54)). This value results from the one out of nine encounter com-



Figure 3. Photooxidation of $(tert-butyl)_4$ -PcZn with CBr₄. Absorbance changes resulting from the photooxidation reaction of $(tert-butyl)_4$ -PcZn with CBr₄ (1 mM in CH₂Cl₂). The solution was deaerated with argon and irradiated with wavelengths greater than 600 nm for 120 s. Note the bleaching of the Pc (~350, 610 and 680 nm) and the growth of the Pc radical cation at ~440 and 514 nm.

plexes between the excited triplet and oxygen that results in the production of singlet oxygen (55).

Photooxidation of Pc

Prompted by the study of Pc photooxidation published by Nyokong et al. (56) (t-butyl)₄-PcZn was photolyzed in CH_2Cl_2 with carbon tetrabromide (1 mM). As shown in Fig. 3, irradiation of an argon-saturated solution of (t-butyl)₄-PcZn and CBr₄, with wavelengths of light greater than 600 nm, caused bleaching of the Pc absorbance bands at 350, 610 and 680 nm and a concurrent growth of absorbance bands at 446 and 514 nm. This behavior was consistent with the formation of the Pc radical cation $[(t-Bu)_4-ZnPc^+]$, or $(t-Bu)_4-ZnPc^+$ $Bu_{4}-ZnPc(-1)$] resulting from the photoinduced transfer of an electron to CBr₄, as shown in Nyokong et al. (56). Subsequent photolyses monitored on a spectrophotometer with near IR capabilities confirmed the growth of an additional band at 840 nm, which was also observed by Nyokong et al. Control reactions done with light but no acceptor, or with acceptor but without light, did not produce the observed absorbance changes. The addition of a reductant such as sodium dithionite $(Na_2S_2O_4)$ or phenylhydrazine returned the original MPc spectrum. Nyokong et al. claim that the electron is removed from the macrocyclic ring of the Pc triplet state (1.1-1.3 eV above the ground state, 1.13 eV for (tbutyl)₄-PcZn-from the wavelength of phosphorescence emission) rather than from the central metal ion (in the case of Zn) (56).

Stern–Volmer quenching kinetics (57) were measured by plotting the ratios of (t-butyl)₄-PcZn fluorescence intensities in the absence and presence of various quencher concentrations *versus* the concentration of quencher (0–10 mM). The Stern–Volmer quenching constant (K_{sv}) was then calculated as the slope of the least-squares linear regression of fluorescence quenching ([I₀/I] – 1) *versus* quencher concentration ([Q]). Using the measured fluorescence lifetime (τ_F) value of 3.63 ns (see Table 2) and Eq. 6 below, the rate constant for

MPc (kc		E _T (kcal/mol)	Carbon t	etrabromide	MV		
	ΔE ₀₀ (kcal/mol)		$\Delta G^{\circ} (\Delta E_{00})$ (kcal/mol)	$\Delta G^{\circ} (E_{T})$ (kcal/mol)	$\frac{\Delta G^{\circ} (\Delta E_{00})}{(\text{kcal/mol})}$	$\Delta G^{\circ} (E_{T})$ (kcal/mol)	
$(\text{Diol})(t-\text{Bu})_{3}-\text{PcH}_{2}$	40.73	28.68	-30 (-1.3 eV)	-18 (-0.79 eV)	-23 (-1.0 eV)	-11 (-0.48 eV)	
(Diol)(t-Bu) ₃ -PcZn	42.05	25.76	-32(-1.4 eV)	-16(-0.67 eV)	-25(-1.1 eV)	-8.4(-0.36 eV)	
(Diol)(t-Bu) ₃ -PcPd	41.65	27.60	-31(-1.4 eV)	-17(-0.75 eV)	-24(-1.1 eV)	-10(-0.44 eV)	
$(t-Bu)_{4}$ -PcH ₂	40.79	28.68	-30(-1.3 eV)	-18(-0.79 eV)	-23(-1.0 eV)	-11(-0.48 eV)	
(t-Bu) ₄ -PcZn	42.17	26.00	-31(-1.4 eV)	-15(-0.66 eV)	-24(-1.0 eV)	-8.0(-0.34 eV)	
(t-Bu) ₄ -PcPd	43.06	27.81	-32(-1.4 eV)	-17 (-0.72 eV)	-25 (-1.1 eV)	-9.5 (-0.41 eV)	

Table 4. Free energy values for electron transfer to carbon tetrabromide and MV

fluorescence quenching (k_q) was determined to be 8.03 \times 10⁹ M^{-1} s⁻¹.

$$k_{\rm q} = K_{\rm sv}/\tau_{\rm F}.$$
 (6)

The quantum yield for photooxidation was measured using steady-state irradiation and the photoaquation reaction of $Cr(urea)_6Cl_3$ for actinometry (58). By monitoring the decay of Pc absorbance at 672 nm with 1 mM CBr₄ for a given intensity of light, the quantum yield was determined to be 0.012 ± 0.003 . Because 1 mM CBr₄ quenches 2.8% of the singlet states formed (from the Stern-Volmer analysis above), the quantum yield can be corrected to 0.429. This correction neglects any triplet-state quenching (not determined for this reaction) and therefore may be overestimated.

The same photooxidation reaction was investigated with the other symmetrically substituted, $(tert-butyl)_4$ -Pc (M = H₂ and Pd) and the unsymmetrically substituted (diol)(t-Bu)₃-PcM. No Pc radical cation absorbance was detected for any of these other MPc under steady-state irradiation. The only effect was a bleaching of the ground-state MPc absorbance bands. Nevertheless, the CBr₄ was quenching the singlet states of the Pc with quenching constants (k_q) estimated from the equation below:

$$I_0/I \approx 1 + k_a \tau[Q] \tag{7}$$

where I and I₀ are the fluorescence intensities with and without quencher, respectively, k_q is the rate constant for quenching, τ is the lifetime of the excited singlet state (from Table 2) and [Q] is the concentration of the quencher (CBr₄, in this case). The values of k_q for the unsymmetrically substituted (diol)(*t*-Bu)₃-PcM were determined to be 2.0 × 10⁸, 7.3 × 10⁹ and 2.7 × 10⁸ M^{-1} s⁻¹ for M = H₂, Zn and Pd, respectively, using [Q] = 0.10 *M*.

The ground-state oxidation potential of $(t-Bu)_4$ -PcZn from Table 1 is 0.396 V (vs SCE) in CH₂Cl₂ and the reduction potential of CBr₄ is -0.3 V (vs SCE) (56). Using Eq. 1 and the triplet energy level estimated from the phosphorescence wavelength, the free energy for electron transfer (ΔG^0) is -15 kcal/mol (-0.66 eV) for reaction from the excited triplet state. Although the free energy for reaction from the excited singlet state (calculated from the 0–0 excitation energy, ΔE_{00}) is twice that for the triplet (-31 kcal/mol), the Stern-Volmer analysis above shows that only 2.8% of the singlets are quenched with a quencher (CBr₄) concentration of 1 mM. However, using the triplet lifetime given in Table 2 (τ_T = 41.1 μ s) and the relationship in Eq. 4, the same concentration of CBr₄ will quench 99.8% of the triplet states, assuming a diffusion-controlled quenching rate. The free energy of electron transfer calculated for the other five MPc with both carbon tetrabromide and methyl viologen, using the singlet energy values ($\Delta G^0[\Delta E_{00}]$) and triplet energy values ($\Delta G^0[E_T]$), is shown in Table 4. Whereas the free energy for electron transfer from the singlet state is nearly isoenergetic for all six MPc, reaction from the triplet state is most exergonic for the free-base compounds. The (*t*-Bu)₄-PcZn, which reacted so readily, has the least exergonic free energy value. Clearly, the reactivity pattern observed with this set of compounds toward electron transfer to CBr₄ is governed by more than thermodynamics.

Nanosecond laser flash photolysis was then used to determine whether the back electron transfer (or other) reaction was occurring on a timescale that was too fast for observation of any net radical cation formation by steady-state irradiation. If the radical ion pair recombined (or reacted to form products) after diffusion out of the solvent cage, but before the ground-state absorption spectrum could be measured, then no radical cation would be observed. The flash photolysis of (diol)(t-Bu)₃-PcM and (t-Bu)₄-PcH₂ (and Pd), with 1 mM CBr₄ in CH₂Cl₂, gave the same triplet-triplet absorbances found above, but with a higher relative intensity. Although the triplet quenching constants were not specifically determined, it appears that the CBr₄ only enhances the formation of excited triplet states (by the "heavy-atom effect") for these Pc without subsequent net electron transfer. If any electron transfer is occurring, the rate of the forward reaction (including the cage escape step) must be exceeded by either the rate of back electron transfer or the rate of cation radical quenching through reaction to form products. Electron transfer to CBr_4 has also been observed by Stiel et al. with $(t-buty)_4$ -PcMg in chloroform (59).

The same photooxidation behavior observed with (*t*-butyl)₄-PcZn and carbon tetrabromide was also observed with carbon tetrachloride (CCl₄). Addition of phenylhydrazine reduced the Pc radical cation and returned the normal groundstate absorption spectrum. The reduction potential of CCl₄ (-0.47 vs SCE) (60) is lower than that for CBr₄, but the former should not induce the heavy atom effects of the latter. Steady-state irradiation (>600 nm), with (*t*-butyl)₄-PcZn, (O \land O)(*t*-butyl)₃-PcZn and (neopentoxy)₄-PcZn in CCl₄ (as the solvent), lead to radical cation formation within 4 min. The other MPc gave either bleaching ([diol][*t*-butyl]₃-PcZn) or no reaction ([*t*-butyl]₄-PcH₂ and -Pd). Although the free energy for electron transfer (from Eq. 1 above) is exergonic for all six MPc (only slightly less than that for methyl viologen, Table 4), examination of the triplet quenching behav-



Figure 4. Appearance of MV^+ at 395 nm. Reduced $MV (MV^+)$ produced following excitation of $(diol)(t-butyl)_{3}$ -PcZn (at nm, 65 μM) in dry, nitrogen-saturated acetonitrile containing MV bis-(hexafluorophosphate) (0.5 mM).

ior suggests an explanation for the observed reactivity pattern. The quenching constants (k_q) of the Pc triplet decay, as with ${}^{3}O_2$ above (Table 3) reveal very inefficient quenching $(10^4-10^5 M^{-1} s^{-1})$ for all but (t-butyl)_4-PcZn and (t-butyl)_4-PcPd $(10^6 M^{-1} s^{-1})$. However, the triplet lifetime (τ_T) for the latter is only 10 μ s compared to the 41 μ s for the former (Table 2). Comparison of the triplet absorbance values with and without quencher indicated no significant change in the amount of triplet states formed, thus confirming the expectations discussed above. Carbon tetrachloride did not quench the fluorescence of the longest-lived singlet state ([*t*-butyl]_4-PcH₂, 9.00 ns) at concentrations of up to 30 mM, sufficient to quench greater than 99% of all the triplet states and 50% of all the singlet states (except [*t*-butyl]_4-PcPd).

Photoinduced electron transfer reactions were also examined with *p*-chloranil (2,3,5,6-tetrachloro-1,4-benzoquinone) and methyl viologen (1,1'-dimethyl-4,4'-biopyridinium, "paraquat") as electron acceptors. Because steady-state irradiations produced no observable reaction products, the reactions were studied using the nanosecond flash photolysis system described above and in dry acetonitrile to facilitate separation of the radical ion pair and solvation of methyl viologen (MV^{2+}).

Excitation of (diol)(*t*-Bu)₃-PcZn (65 m*M*) with MV·(PF₆)₂ (0.5 m*M*) in dry, nitrogen-saturated acetonitrile, produced a signal at 395 nm (from MV⁺) (61), which increased at the rate of $\sim 2 \times 10^6$ s⁻¹, equivalent to the rate of the Pc triplet decay (Fig. 4). The rate of ³PcZn quenching was observed to be approximately diffusion controlled (2 × 10¹⁰ *M*⁻¹ s⁻¹ for acetonitrile (54)) by comparison of the triplet lifetimes with and without quencher (57).

Lifetime of S* (no quencher):

$$1/t_1 = k_1$$
 (8)

Lifetime of S* (with quencher):

$$l/t_2 = k_1 + k_q[Q]$$

= 1/t_1 + k_q[O] (9)

therefore:

$$k_{\rm q} = 1/[Q](1/t_2 - 1/t_1)$$
 (10)

$$ZnPc \xrightarrow{av} ZnPc^*$$
 (11)

$$ZnPc^* + MV^{2+} \rightarrow ZnPc^{++} + MV^{++}$$
(12)

$$ZnPc^{++} + MV^{++} \xrightarrow{\sim} ZnPc + MV^{2+}$$
(13)



Figure 5. Difference absorption spectra of $(diol)(t-butyl)_3$ -PcZn with 0.5 mM MV²⁺ (in acetonitrile) 36, 324 and 648 ns after the excitation pulse.

Equations 11–13 show the basic steps involved in this reaction. The reciprocal of the MV⁺ lifetime (1/t) values were plotted against various concentrations of the MV²⁺ quencher (1–10 mM). The slope of a line drawn through those points yielded a triplet quenching constant (k_q) of 2.3 $\times 10^8 M^{-1} s^{-1}$. The bimolecular decay (Eq. 13) was analyzed by following the decay of both MV^{+.} (at 395 nm) and ZnPc^{+.} (at 840 nm, a wavelength unique to that species) (62). By fitting each decay curve with a second-order rate algorithm, an observed rate constant of approximately 5.1 $\times 10^5 s^{-1}$ was obtained. Because the rate of decay is equivalent for each species

$$-d[MV^{+}]/dt = -d[ZnPc^{+}]/dt = k[MV^{+}[ZnPc^{+}]. (14)$$

If the concentrations of the two radical cations formed are equivalent at any time (t)

$$-d[MV^{+}]/dt = k[MV^{+}]^{2}.$$
 (15)

Integration of this rate equation and substitution of $[MV^{+}]$ by OD₁/ ϵ l (using Beer's Law) gives

$$1/OD_{t} = 1/OD_{t=0} + (k/\epsilon l)_{t}.$$
 (16)

By plotting $1/OD_1$ versus time, the slope of the line gives the value of the observed rate constant $(K = k/\epsilon I)$. If the extinction coefficients of the radical cations are known, then the actual bimolecular rate constant can be calculated. Using the values of $\epsilon_{MV}^+ = 3.8 \times 10^4 M^{-1} \text{ cm}^{-1}$ (at 395 nm) (63) and $\epsilon_{ZnPc^{++}} \approx 3 \times 10^4 M^{-1} \text{ cm}^{-1}$ (estimated from the molar absorptivity spectrum of ZnPc^+, at 395 nm) (56) the total extinction coefficient becomes $\mathbf{e} = 6.8 \times 10^4 M^{-1} \text{ cm}^{-1}$. A value of $3.5 \times 10^{10} M^{-1} \text{ s}^{-1}$ is then obtained for the rate constant (k). Therefore, the recombination of MV⁺⁻ and ZnPc⁺⁻ (to MV²⁺ and ZnPc) occurs slightly faster than the diffusion-controlled rate for acetonitrile (2 $\times 10^{10} M^{-1} \text{ s}^{-1}$) (54).

The difference absorption spectra for this reaction (Fig. 5) show mostly Pc triplet, 36 ns after the excitation pulse, followed by the appearance of the reduced MV^+ (at 395 nm) and the oxidized ZnPc⁺⁻ (at 440, 510 and 840 nm—consistent with the (*tert*-butyl)₄-PcZn⁺⁻ formed with CBr₄ above),



Figure 6. Difference absorption spectrum of $([diol][t-butyl]_3-PcZn)^+$ (0–0.2 µs after excitation pulse). Methyl viologen concentration is increased to 10 mM to quench the initial ³PcZn formed after excitation. Photolysis is run in oxygen-saturated acetonitrile to quench any MV⁺.

340 and 648 ns after the excitation pulse. By increasing the $[MV^{2+}]$ to 10 m*M*, the initial ³PcZn absorbance is quenched. Running the photolysis in an air-equilibrated solution ($[O_2] = 1.91 \text{ m}M$ (44)) quenches the MV⁺ formed and leaves only the ZnPc⁺⁻ difference spectrum (Fig. 6). Unfortunately, steady-state irradiation of (diol)(*t*-Bu)₃-PcZn with MV²⁺ in acetonitrile produced no discernible change in the ground-state absorption spectrum.

DISCUSSION

Photophysical measurements

The values listed in Table 2 compare the properties of the lowest-lying, ligand-centered singlet and triplet states for the unsubstituted (literature) and substituted MPc. In general, the values measured for the symmetrically and unsymmetrically substituted MPc correlate well with the literature values for the unsubstituted MPc. As the central substituent is changed from H_2 to Zn to Pd, the fluorescence emission wavelength is blue-shifted (except for [diol] [t-Bu]₃-PcPd), and the values for $\Phi_{\rm F}$ and $\tau_{\rm F}$ decrease. The decrease in $\Phi_{\rm F}$ is generally concurrent with the increase in Φ_T and is expected from the "heavy atom effect" as the central substituent is changed from H₂ to Zn to Pd (53). The decrease in τ_F is expected as the rate of intersystem crossing (k_{isc}) increases, hastening the depopulation of the excited singlet state. Because the fractions of excitation energy resulting in fluorescence ($\Phi_{\rm F}$) and in triplet formation (Φ_T) do not add up to unity, the remaining excitation is presumed to be dissipated as heat (nonradiative decay, $k_{\rm nr}$). This, of course, assumes that no photochemical reactions are occurring from the excited state. The rate of nonradiative decay can be measured using a calorimetric technique, such as photoacoustic calorimetry (64,65) or thermal lensing, (21,66) but was not performed here.

The value of Φ_T for (diol)(t-butyl)₃-PcZn in Table 2 is conspicuously low when compared to the Φ_{Δ} values in Table 3, and to the triplet quantum yield for the symmetrical (tbutyl)₄-PcZn. Given the relative accuracy with which these values were obtained, along with the obviously low value for this suspect number, it is assumed that the measurement was in error and should be repeated in a more rigorous study. A thorough explanation of possible sources of error for both sets of quantum yield values may be found in the author's dissertation (3).

The potential for photodynamic therapy (PDT) efficacy

The three (diol)(t-butyl)₃-PcM chromophores were tested as potential PDT sensitizers by examining the inhibition of the mitochondrial enzyme cytochrome c oxidase (67). Although the unsymmetrically substituted MPc possess significant quantum yields for singlet oxygen production (Φ_{Λ}), as well as sufficient solubility in biologically acceptable media, such as EtOH and DMSO, they did not inhibit the activity of mitochondrial cytochrome c oxidase. This lack of activity is attributable to an assumed low uptake by the mitochondria (as indicated by the precipitate formed after centrifugation) and to fluorescence quenching in the mitochondrial buffer. The quenching is due to aggregate formation and/or a buffer component (presumably bovine serum albumin, BSA), which effectively competes with ground-state oxygen for the sensitizer's excited-state energy. The latter significantly reduces the Φ_{A} values to near zero. Furthermore, from the absorption and emission spectra of the MPc in buffer, and because no emission from ${}^{1}O_{2}$ could be detected in the buffer solution alone, the aggregate formed in the mitochondrial buffer precludes any significant formation of ¹O₂. Therefore, it is clear that the design of potential PDT sensitizers with good solubility properties and Φ_{Δ} values does not necessarily ensure sufficient PDT efficacy in a biologically relevant medium.

Photooxidation reactions

Although reversible electron transfer to CBr₄ and CCl₄ was observed only with (t-butyl)₄-PcZn, presumably as a result of an effective combination of triplet quantum yield and lifetime, the ground-state absorbance bleaching with the other macrocycles suggests a reaction with the acceptor. This reaction may take place after electron transfer, with either half of the disproportionated anion radical, to produce a species with little or no visible absorption. Using MV and p-chloranil as electron acceptors provided evidence of Pc radical cation formation, but only the zinc-containing macrocycles were sufficiently soluble to determine the kinetics involved. Axial ligation of the solvent to the metal center of a Pc prevents interfacial stacking and thereby enhances solubility. Although the nitrogen lone pair electrons of acetonitrile are not as donating as those of pyridine, some coordination may be expected to take place with metals (such as Zn^{2+}) that will accept them. The zinc compounds were observed to be slightly more soluble than the free-base and palladium compounds in terms of chromatography. Thus, through a presumed coordination with the solvent, they may remain more soluble in photoinduced electron transfer reactions as well.

The lack of reactivity observed for the unsymmetrically substituted $(diol)(t-butyl)_3$ -PcM and the $(t-butyl)_4$ -PcM (M = H₂ and Pd) toward photoinduced electron transfer with acceptors such as CBr₄ and CCl₄ is not sufficiently explained by comparison of the free energy values shown in Table 4.

Although the excited triplet states of MPc have an average of 0.62 eV less energy than their singlet counterparts (Table 4), none of the free energy values for electron transfer is very different from the other. However, examination of the triplet-state properties shown in Table 2 reveals that only (*t*butyl)₄-PcZn has the highest combination of triplet quantum yield ($\Phi_T = 0.24$) and lifetime ($\tau_T = 41.1$ ms). The palladium compounds have as high (or higher) triplet quantum yields but shorter triplet lifetimes. The other zinc and free-base compounds have longer triplet lifetimes but smaller triplet quantum yields.

The energy of the excited state must not only be high enough to facilitate electron transfer, but the reaction (specifically the cage escape and ion pair separation steps) must also occur at a rate that exceeds both the rates of back electron transfer (returning to the original ground-state reactants) and other reactions (e.g. decay, quenching by oxygen, etc.). If electron transfer does occur, the ions may not escape the solvent cage and separate to become free ions (see the Introduction) before they recombine and therefore will not be observed experimentally. However, ions that do escape the solvent cage will not likely recombine due to the fast disproportionation of CBr_4^{-1} to CBr_3^{-1} and Br^{-1} . Unfortunately, the advantage of this disproportionation is diminished by the possible reaction of the donor radical cation (MPc⁺) with either CBr₃ or Br⁻. Such a reaction, if rapid and efficient, would alter the absorption spectrum of the radical cation and obscure its presence to the researcher. The bleaching of the ground-state absorbance bands, when MPc other than (t-butyl)₄-PcZn were photolyzed with either CBr₄ or CCl₄, suggests that reaction of the radical cation, if formed, with the disproportionated acceptor products was occurring.

Electron transfer to MV²⁺ was expected to give an observable Pc radical cation due to the charge repulsion that occurs upon formation of two positively charged species (MPc⁺⁺ and MV⁺). This charge repulsion should be the driving force behind a favorable cage escape rate over the back electron transfer rate. Using the Rehm/Weller equation (Eq. 1) discussed in the Introduction, all six MPc have an exergonic free energy for electron transfer (ΔG^0) to MV (Table 4). These values are calculated from the reduction potential for MV in CH₃CN (-0.44V vs SCE) (68), the MPc oxidation potentials from Table 1, and the ΔE_{00} values estimated from the intersection of the absorption and emission spectra. Given that the metallophthalocyanines examined are expected to react preferentially from the triplet state when excited with wavelengths greater than 600 nm (10,56), it may be more germane to use the triplet energy (E_T) values for the MPc instead of the 0–0 excitation energy (ΔE_{00}) values. Although the E_T values were not determined specifically, the wavelengths of phosphorescence for the Zn(II) and Pd(II) chelates may be used as an approximation. For the free-base compounds, the value determined by McVie et al. for the unsubstituted H_2Pc (in chloronaphthalene) was used (27). The authors obtained this value by bracketing the rates of energy transfer to/from various quenchers of known triplet energy (e.g. β -carotene, perylene, anthracene). The less exergonic ΔG^0 values resulting from the E_T values [ΔG^0 (E_T)] instead of the singlet energy ΔE_{00} values $[\Delta G^0 (\Delta E_{00})]$ reflect the lower energy available to induce the electron transfer reaction.

The literature has many examples of electron transfer using porphyrins and Pc as sensitizers. In most cases, though, back electron transfer, from the radical ion pair [MPc^{+,}/A^{-,}] to the ground-state reactants, is prevented using a sacrificial donor (such as EDTA, triethanolamine or cysteine) that reacts irreversibly with the radical anion of the electron acceptor (10,63,69,70). Electron transfer between an excited MPc and an electron acceptor, without the addition of any sacrificial donors, has been observed only occasionally (9,71,72). Usually, these positive results come from the appropriate balance of cage escape and back electron transfer rates, as well as continued solubility throughout the course of the reaction.

Unsymmetrically substituted MPc (either AB₃ or other configuration) have a great potential in applications such as PDT. It has already been shown that the MPc are effective photosensitizers both in vitro and in vivo (73). Through systematic modification of the central metal, its axial ligands and the peripheral substituents, series of macrocycles may be developed in order to investigate the variety of mechanisms that have been proposed for the photodynamic action. Subcellular localization has been a constant source of frustration for many researchers working with the porphyrinand Pc-based photosensitizers. While a compound may be very effective in vitro, in vivo application sometimes leads to reduced (or even enhanced) effectiveness. Although model systems such as the octanol/water partition coefficient can give investigators an idea of a compound's localization behavior, these are approximations at best. A series of rationally designed compounds, which vary in one and only one property (or at least minimal variation in all other properties), is needed in order to systematically understand the manner in which changes in structure affect localization, singlet oxygen production and PDT efficacy. It is hoped that, through the initial studies performed here, a better understanding of the photochemical mechanisms involved with PDT and photoinduced electron transfer may be gained.

Acknowledgements—The authors are indebted to Drs. Steve Atherton and Elizabeth Gaillard for assistance with the photophysical measurements, Scott Gibson (Dept. of Biochemistry) for assistance with the cytochrome c oxidase assay and Rachael Kipp for assistance with the Pc syntheses. Funding was kindly provided by the National Institutes of Health (grant CA48961) and fellowships from Bristol-Myers Squibb and Sherman Clarke.

REFERENCES

- Braun, A. and J. Tchernic (1907) Über die produkte der einwirkung von acetanhydrid auf phthalamid. Ber. Deut. Chem. Ges. 40, 2709-2714.
- Lever, A. B. P. (1965) The phthalocyanines. Adv. Inorg. Chem. Radiochem. 7, 27-114.
- 3. Lawrence, D. S. (1995) Studies of picketfence porphyrins and substituted metallo-phthalocyanines. Ph.D. Dissertation, University of Rochester, Rochester, NY.
- Ferraudi, G. (1989) Photochemical properties of metallophthalocyanines in homogeneous solution. In *Phthalocyanines: Properties and Applications*, Vol. 1 (Edited by C. C. Leznoff and A. B. P. Lever), Chapter 4. VCH, New York.
- Wasielewski, M. R. (1992) Photoinduced electron transfer in supramolecular systems for artificial photosynthesis. *Chem. Rev.* 92, 435-461.
- Kavarnos, G. J. and N. J. Turro (1986) Photosensitization by reversible electron transfer: theories, experimental evidence and examples. *Chem. Rev.* 86, 401–449.

- 7. Rehm, D. and A. Weller (1970) Kinetics of fluorescence quenching by electron and H-atom transfer. *Isr. J. Chem.* 8, 259–271.
- 8. Eberson, L. (1987) Electron Transfer Reactions in Organic Chemistry, pp. 27, 157. Springer Verlag, New York.
- Lever, A. B. P., S. Licoccia, B. S. Ramaswamy, S. A. Kandil and D. V. Stynes (1981) Phthalocyanine sensitized reduction of methyl viologen using visible light. *Inorg. Chim. Acta* 51, 169– 176.
- Darwent, J. R., P. Douglas, A. Harriman, G. Porter and M.-C. Richoux (1982) Metal phthalocyanines and porphyrins as photosensitizers for reduction of water to hydrogen. *Coord. Chem. Rev.* 44, 83-126.
- Metez, J., O. Schneider and M. Hanack (1984) Synthesis and properties of substituted (phthalocyanato)iron and -cobalt compounds and their pyridine adducts. *Inorg. Chem.* 23, 1065–1071.
- 12. Dallacker, F. and H. Zegers (1965) Zur einfürhrung von schwefel in abkömmlinge des brenzcatechin-methylenäthers. Just. Lieb. Ann. Chem. 689, 156–162.
- Mikhalenko, S. A., S. V. Barkanova, O. L. Lebedev and E. A Luk'yanets (1971) Phthalocyanines and related compounds IX. Synthesis and electronic absorption spectra of tetra-4-t-butylphthalocyanines. J. Gen. Chem. USSR (Engl. Transl.) 41, 2770– 2773; Zh. Obshch. Khim. 41, 2735–2739.
- Gaspard, S. and P. Maillard (1987) Structure des phtalocyanines tetra tertio-butylees: mechanisme de la synthese. *Tetrahedron* 43, 1083-1090.
- 15. Mercer-Smith, J. A. (1978) Photochemical studies of palladium (II) and platinum (II) porphyrins. Ph.D. Dissertation, University of North Carolina, Chapel Hill.
- Lever, A. B. P., E. R. Milaeva and G. Speier (1993) The redox chemistry of metallophthalocyanines in solution. In *Phthalocyanines: Properties and Applications*, Vol. 3 (Edited by C. C. Leznoff and A. B. P. Lever), p. 8. VCH, New York.
- Gagne, R. R., C. A. Koval and G. C. Lisensky (1980) Ferrocene as an internal standard for electrochemical measurements. *Inorg. Chem.* 19, 2854–2855.
- 18. Nykong, T., Z. Gasyna and M. J. Stillman (1987) Phthalocyanine π -cation-radical species: photochemical and electrochemical preparation of $[ZnPc(-1)]^+$ in solution. *Inorg. Chem.* **26**, 548–553.
- Teuchner, K., A. Pfarrherr, H. Stiel, W. Freyer and D. Leupold (1993) Spectroscopic properties of potential sensitizers for new photodynamic therapy start mechanisms via two-step excited electronic states. *Photochem. Photobiol.* 57, 465–471.
- 20. Rodgers, M. A. J. and P. T. Snowden (1982) Lifetime of O_2 ($^{1}\Delta_{g}$) in liquid water as determined by time-resolved infrared luminescence measurements. J. Am. Chem. Soc. 104, 5541–5543.
- 21. Rossbroich, G., N. A. Garcia and S. E. Braslavsky (1985) Thermal-lensing measurements of singlet molecular oxygen $({}^{1}\Delta_{g})$: quantum yields of formation and lifetimes. J. Photochem. **31**, 37-48.
- 22. Schmidt, R., C. Tanielan, R. Dunsbach and C. J. Wolff (1994) Phenalenone, a universal reference compound for the determination of quantum yields of singlet oxygen O_2 (${}^{1}\Delta_g$) sensitization. *Photochem. Photobiol.* **79**, 11–17.
- Gorman, A. A., I. Hamblett and M. A. J. Rodgers (1984) Timeresolved luminescence measurements of triplet-sensitized singlet-oxygen production: variation in energy-transfer efficiencies. J. Am. Chem. Soc. 106, 4679–4682.
- Ford, W. E., B. D. Rihter, M. E. Kenney and M. A. J. Rodgers (1989) Photoproperties of alkoxy-substituted phthalocyanines with deep-red optical absorbance. *Photochem. Photobiol.* 50, 277-282.
- 25. Carmichael, I. and G. L. Hug (1986) Triplet-triplet absorption spectra of organic molecules in condensed phases. J. Phys. Chem. Ref. Data 15, 1-250.
- Carmichael, I., W. P. Helman and G. L. Hug (1987) Extinction coefficients of triplet-triplet absorption spectra of organic molecules in condensed phases: a least-squares analysis. J. Phys. Chem. Ref. Data 16, 239-260.
- 27. McVie, J., R. S. Sinclair and T. G. Truscott (1978) Triplet states

of copper and metal-free phthalocyanines. J. Chem. Soc., Faraday Trans J 74, 1870-1879.

- Turro, N. J. (1978) Modern Molecular Photochemistry, pp. 103– 104. Benjamin/Cummings, Reading, MA.
- Hurley, J. K., N. Sinai and H. Linschitz (1983) Actinometry in monochromatic flash photolysis: the extinction coefficient of triplet benzophenone and quantum yield of triplet zinc tetraphenyl porphyrin. *Photochem. Photobiol.* 38, 9-14.
- 30. Brauer, G. (1962) Handbook of Preparative Inorganic Chemistry. Ferdinand Enke Verlag, Stuttgart.
- McKeown, N. B., I. Chambrier and M. J. Cook (1990) Synthesis and characterization of some 1,4,8,11,15,18,22,25-octa-alkyland 1,4,8,11,15,18-hexa-alkyl-22,25-bis(carboxypropyl)phthalocyanines. *Chem. Soc. Perkin Trans I*, 1169–1177.
- Piechocki, C. and J. Simon (1985) Synthesis of a polar discogen. A new type of discotic mesophase. J. Chem. Soc. Chem. Commun. 259-260.
- Leznoff, C. C. and T. W. Hall (1982) The synthesis of a soluble, unsymmetrical phthalocyanine on a polymer support. *Tetrahedron Lett.* 23, 3023–3026.
- 34. Wöhrle, D. and G. Krawczyk (1986) Polymeric bound porphyrines and their precursors, 3: photoredox properties of combined moieties of porphyrine and phthalocyanine, covalently bound to polystyrene. *Makromol. Chem.* 187, 2535–2544.
- Allcock, H. R. and T. X. Neenan (1986) Synthesis of polyphosphazenes bearing covalently linked copper phthalocyanine units. *Macromolecules* 19, 1495–1501.
- Kobayashi, N., R. Kondo, S. Nakajima and T. Osa (1990) New route to unsymmetrical phthalocyanine analogues by the use of structurally distorted subphthalocyanines. J. Am. Chem. Soc. 112, 9640-9641.
- Kobayashi, N. (1991) A rigid, laterally bridged binuclear subphthalocyanine: the first dimer of aromatic macrocyclic complexes containing boron. J. Chem. Soc. Chem. Commun., 1203– 1205.
- Kasuga, K., T. Idehara, M. Handa and K. Isa (1992) Preparation of unsymmetrical phthalocyanine by means of a ring expansion of subphthalocyanine. *Inorg. Chim. Acta* 196, 127–128.
- Weitemeyer, A., H. Kliesch and D. Wöhrle (1995) Unsymmetrically substituted phthalocyanine derivatives via a modified ring enlargement reaction of unsubstituted subphthalocyanine. J. Org. Chem. 60, 4900–4904.
- Lever, A. B. P., E. R. Milaeva and G. Speier (1993) The redox chemistry of metallophthalocyanines in solution. In *Phthalocyanines: Properties and Applications*, Vol. 3 (Edited by C. C. Leznoff and A. B. P. Lever), pp. 12–17. VCH, New York.
- Stallings, M. D., M. M. Morrison and D. T. Sawyer (1981) Redox chemistry of metal-catechol complexes in aprotic media.
 Electrochemistry of substituted catechols and their oxidation products. *Inorg. Chem.* 20, 2655–2660.
- 42. Ferraudi, G. (1989) Photochemical properties of metallophthalocyanines in homogeneous solution. In *Phthalocyanines: Properties and Applications*, Vol. 1 (Edited by C. C. Leznoff and A. B. P. Lever), pp. 300–301. VCH, New York.
- Vincett, P. S., E. M. Voigt and K. E. Rieckhoff (1971) Phosphorescence and fluorescence of phthalocyanines. J. Chem. Phys. 55, 4131-4140.
- 44. Murov, S. L. (1973) Handbook of Photochemistry, p. 89. Dekker, New York.
- 45. Turro, N. J. (1978) Modern Molecular Photochemistry, p. 591. Benjamin/Cummings, Reading, MA.
- 46. Truscott, T. G., E. J. Land and A. Sykes (1973) The *in vitro* photochemistry of biological molecules—III. Absorption spectra, lifetimes, and rates of oxygen quenching of the triplet states of β-carotene, retinal and related polyenes. *Photochem. Photobiol.* 17, 43–51.
- 47. Conn, P. F., C. Lambert, E. J. Land, W. Schlach and T. G. Truscott (1992) Carotene-oxygen radical interactions. *Free Radical Res. Commun.* 16, 401–408.
- Richards, J. T. and J. K. Thomas (1970) Effect of solvent on the flash photolysis and laser photolysis of N,N,N',N'-tetramethyl-paraphenylene diamine in solution. *Trans. Faraday Soc.* 66, 621-632.
- 49. Amand, B. and R. Bensasson (1975) Determination of triplet

quantum yields by laser flash absorption spectroscopy. Chem. Phys. Lett. 34, 44-48.

- Bensasson, R. and E. J. Land (1978) In *Photochemical and Photobiological Reviews*, Vol. 3 (Edited by K. C. Smith) pp. 163– 191. Plenum, New York.
- Bensasson, R., C. R. Goldschmidt, E. J. Land and T. G. Truscott (1978) Laser intensity and the comparative method for determination of triplet quantum yields. *Photochem. Photobiol.* 28, 277-281.
- 52. Gorman, A. A. and M. A. J. Rodgers (1989) Singlet oxygen. In *The Handbook of Organic Photochemistry*, Vol. 2 (Edited by J. C. Scaiano), pp. 229–247. CRC, Boca Raton, FL.
- Turro, N. J. (1978) Modern Molecular Photochemistry, pp. 125– 126, 192. Benjamin/Cummings, Reading, MA.
- 54. Turro, N. J. (1978) Modern Molecular Photochemistry, p. 314. Benjamin/Cummings, Reading, MA.
- 55. Saltiel, J. and B. W. Atwater (1988) Spin-statistical factors in diffusion-controlled reactions. Adv. Photochem. 14, 1-90.
- 56. Nyokong, T., Z. Gasyna and M. J. Stillman (1986) Photooxidation of phthalocyanines (photoinduced reactivity of the triplet state). In *Porphyrins: Excited States and Dynamics*, ACS Symposium Series 321 (Edited by M. Gouterman, P. M. Rentzepis and K. D. Straub), pp. 309–327. American Chemical Society, Washington, DC.
- Turro, N. J. (1978) Modern Molecular Photochemistry, pp. 245– 248. Benjamin/Cummings, Reading, MA.
- Wegner, E. E. and A. W. Adamson (1966) Photochemistry of complex ions. III. Absolute quantum yields for the photolysis of some aqueous chromium(III) complexes. Chemical actinometry in the long wavelength visible region. J. Am. Chem. Soc. 88, 394-404.
- 59. Stiel, H., K. Teuchner, A. Paul, W. Freyer and D. Leupold (1°94) Two-photon excitation of alkyl-substituted magnesium phthalocyanine: radical formation via higher excited states. J. Photochem. Photobiol. A Chem. 80, 289-298.
- Meites, L., P. Zuman, W. J. Scott, B. H. Campbell and A. M. Kardos (1974) *Electrochemical Methods*. John Wiley & Sons, New York.

- 61: Trudinger, P. A. (1970) On the absorbancy of reduced methyl viologen. Anal. Biochem. 36, 222-225.
- 62. Gaillard, E. R. (1990) A kinetic study of several reactions involving excited state sigma bond cleavage. Ph.D. Dissertation, University of Texas at Austin.
- 63. Darwent, J. R. (1980) Photoreduction of methyl viologen in micellar solutions sensitized by zinc phthalocyanine. J. Chem. Soc. Chem. Commun., 805–807.
- 64. Redmond, R. W. (1991) Enhancement of the sensitivity of radiative and non-radiative detection techniques in the study of photosensitization by water soluble sensitizers using a reverse micelle system. *Photochem. Photobiol.* 54, 547-556.
- Braslavsky, S. E. and K. Heihoff (1989) In *The Handbook of Organic Photochemistry*, Vol. 1 (Edited by J. C. Scaiano), pp. 327–355. CRC, Boca Raton, FL.
- Fuke, K., M. Ueda and M. Itoh (1980) Direct observation of singlet oxygen by a thermal lensing technique. *Chem. Phys. Lett.* 76, 372-374.
- 67. Gibson, S. L. and R. Hilf (1983) Photosensitization of mitochondrial cytochrome c oxidase by hematoporphyrin derivative and related porphyrins. *Cancer Res.* **43**, 4191–4197.
- 68. Sober, H. A. (1968) Handbook of Biochemistry. CRC Press, Cleveland, OH.
- 69. Maillard, P., S. Gaspard, P. Krausz and C. J. Giannotti (1981) Electron transfer reactions between methyl viologen and porphyrins, bis-porphyrins, phthalocyanines, and their metal derivatives. J. Organomet. Chem. 212, 185–191.
- Kasuga, K., H. Hayashi and M. Handa (1991) Photoreduction of methyl viologen with a water-soluble phthalocyanatozinc(II) complex in an aqueous solution. *Chem. Lett.*, 1877–1880.
- Van Vlierberge, B. and G. Ferraudi (1987) Sequential biphotonic processes: photochemical reactivity of phthalocyanine radicals. *Inorg. Chem.* 26, 337–340.
- Darwent, J. R., I. McCubbin and D. Phillips (1982) Excited singlet and triplet state electron-transfer reactions of aluminum(III) sulphonated phthalocyanine. J. Chem. Soc. Faraday Trans. 2 78, 347-357.
- Rosenthal, I. and E. Ben-Hur (1989) Phthalocyanines in photobiology. In *Phthalocyanines: Properties and Applications*, Vol. 1 (Edited by C. C. Leznoff and A. B. P. Lever). VCH, New York.