

# Synthesis and photophysical properties of a new cationic water-soluble Zn phthalocyanine

Daniel A. Fernández<sup>a</sup>, Josefina Awruch<sup>b</sup>, Lelia E. Dicelio<sup>a,\*</sup>

<sup>a</sup> INQUIMAE, Departamento de Química Inorgánica, Analítica y Química Física, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, Pabellón II, Ciudad Universitaria, (1428) Buenos Aires, Argentina

<sup>b</sup> Departamento de Química Orgánica, Facultad de Farmacia y Bioquímica, Universidad de Buenos Aires, Junín 956, (1113) Buenos Aires, Argentina

Received 2 June 1997; accepted 23 September 1997

## Abstract

The synthesis of tetrakis(1,1-dimethyl-2-trimethylammonium)ethylphthalocyaninato Zn(II) tetraiodide **2** – a new cationic phthalocyanine – is reported as well as its photophysical properties in water, relevant for the use of this dye as photodynamic sensitizer. The hydrophobicity of the macrocycle leads to strong aggregation which lowers the fluorescence and singlet oxygen quantum yields of aqueous solutions of **2**. Photophysical parameters agree with those of other Zn phthalocyanines when correction is performed for the fraction of light absorbed by the monomer. © 1997 Elsevier Science S.A.

**Keywords:** Cationic phthalocyanine; Phthalocyanine; Zinc

## 1. Introduction

Photodynamic therapy (PDT) has developed into an important aspect in the biomedical field in the last twenty years. This therapy is based on the administration of photosensitizers capable of being selectively retained by tumors [1]. It is widely accepted that the singlet molecular oxygen ( $O_2(^1\Delta_g)$ ), generated by these sensitizers upon absorption of light, is the reactive species responsible for tumor killing [2,3].

Zinc and aluminium phthalocyanines have been extensively studied for PDT purposes, not only due to their high triplet quantum yields and long triplet lifetimes that lead to favourable yields of  $O_2(^1\Delta_g)$ , but also for their high fluorescence yield [4]. In vivo and in vitro fluorescence detection is usually employed to obtain information about photosensitizer localization and distribution as well as release from tissues [5,6].

The biodistribution and pharmacokinetics of the photosensitizers employed in PDT depend on the structure and the electronic characteristics of the molecule. Hydrophilic sensitizers are characterized by three or more charged substituents which facilitate their solubility in water at physiological pH. Most of these sensitizers are anionic, with sulphonic and carboxylic substituents [7].

Recent studies have shown the important role of the cationic charges in the peripheral substituents of photosensitizers [8]. These dyes can penetrate the nucleus and produce photoinduced damage in DNA. On the other hand, cationic dyes were found to be useful photosensitizers for the inactivation of Gram-negative bacteria [9]. These organisms, in contrast to Gram-positive bacteria, are insensitive when irradiated in the presence of neutral or negatively-charged drugs.

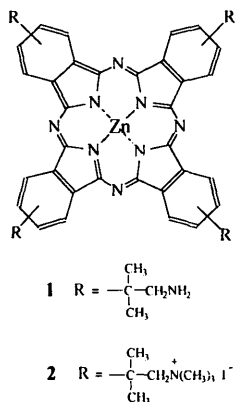
Positively-charged phthalocyanines have been already synthesized and their photochemical properties characterized [10,11]. In this work, we present the new cationic dye tetrakis(1,1-dimethyl-2-trimethylammonium)ethylphthalocyaninato Zn(II) tetraiodide **2**, and its fluorescence and  $O_2(^1\Delta_g)$  yield in aqueous media. A characterization of the dimerization equilibrium was also performed (Scheme 1).

## 2. Experimental

### 2.1. Materials

Solvents were purified according to standard procedures [12]. Diisopropylethylamine (Aldrich), methyl iodide (Merck), methylene blue (Fluka p.a.) and  $D_2O$  (Merck Uva-sol 99.8%) were used as supplied; water was distilled and further purified with a Millipore Milli-Q Water System.

\* Corresponding author.



Scheme 1. Chemical structure of compounds 1 and 2.

Tetracarboxyphthalocyaninato Zn(II) (ZnTCPC) was available in our laboratory – its synthesis has already been described [13].

TLC was carried out using Kodak Chromagram cellulose pre-coated plastic sheets.

## 2.2. Instrumentation

Electronic absorption spectra were determined using a Shimadzu UV-3100/PC spectrophotometer and fluorescence spectra were recorded using a Perkin Elmer LS-5 spectrofluorometer.  $^1\text{H}$  NMR was performed with a Bruker AC 200 spectrometer; the FAB-MS spectrum was obtained using glycerol as matrix, with a ZAB SEQ (VG, Fisons) spectrometer. The infrared spectrum was recorded on an FT-IR Nicolet 510P spectrophotometer. Microanalysis was performed by using a Carlo Erba EA 1108 elemental analyzer.

## 2.3. Synthesis

### 2.3.1. Tetrakis(1,1-dimethyl-2-trimethylammonium)-ethylphthalocyaninato Zn(II) tetraiodide

7.4 mg ( $9 \times 10^{-6}$  mol) of phthalocyanine 1 [14] and 16.5 mg ( $1.28 \times 10^{-4}$  mol) of diisopropylethylamine were dissolved in 2 ml of DMF. Methyl iodide ( $0.25 \times 10^{-3}$  mol) was added, and the mixture was stirred at room temperature for 22.5 h. After 1 had completely reacted, 2.5 ml of diethyl ether was added and the voluminous green precipitate obtained was separated by filtration. The precipitate was washed several times with diethyl ether, dried, dissolved in deionized water and filtered. The solution was lyophilized and 2 was obtained as a green hygroscopic solid (12.7 mg, 97%), mp > 300 °C (Found: C, 46.59; H, 5.23; N, 10.90%).  $\text{C}_{20}\text{H}_{28}\text{N}_4\text{Zn}$  requires C, 46.73; H, 5.23; N, 10.89%;  $\nu_{\text{max}}$  (KBr pellet): 1385, 1111, 617  $\text{cm}^{-1}$ ;  $\delta_{\text{H}}$  (200 MHz;  $\text{D}_2\text{O}$ )

9.36–8.31 (12H, br. aromatic phthalocyanine), 2.96–2.78 (44H, m,  $\text{CH}_2$  and NMe), 2.26 (24H, br.  $\text{CH}_3$ );  $m/z$  (FAB, glycerol) 1415 ( $M-1^+$ , 1%), 989 (10%), 929 (20%), 869 (22%), 811 (38%), 752 (100%).

## 2.4. Dimerization

Absorption spectra were recorded employing quartz cuvettes. It was difficult to obtain accurate spectra at very low concentrations because 2 tends to adsorb to the glass greatly, quartz or plastic cell walls. To minimize the error in the analytical concentration, solutions were prepared by weighing the phthalocyanine directly in the cuvette and adding an accurately measured quantity of water. Concentrations employed were  $9.08 \times 10^{-5}$ ,  $6.81 \times 10^{-5}$ ,  $1.70 \times 10^{-5}$ ,  $1.14 \times 10^{-5}$ ,  $5.67 \times 10^{-6}$ ,  $3.78 \times 10^{-6}$ ,  $1.26 \times 10^{-6}$ ,  $1.05 \times 10^{-6}$ , and  $7.01 \times 10^{-7}$  M. Calculations to obtain  $K_{\text{d}}$  and the absorption coefficients of both monomer and dimer were based on a chemometric analysis of the spectra [15] and a detailed description of the method has been provided elsewhere [16]. The calculated absorption coefficients of the monomer and dimer are shown in Fig. 3.

## 2.5. Fluorescence

The fluorescence quantum yield was determined by comparison with ZnTCPC ( $\Phi_{\text{f}} = 0.32 \pm 0.04$  in dimethylformamide (DMF)) [13] as reference. As emission spectra of sample and reference actually lie in the same wavelength region the uncorrected spectra of air-saturated solution were used to these assays. This type of calculations is normally performed by using equation [17]:

$$\Phi_{\text{f}}^{\text{s}} = \Phi_{\text{f}}^{\text{r}} \frac{I_{\text{f}}^{\text{s}} \left( \frac{1-10^{-A^{\text{s}}}}{1-10^{-A^{\text{r}}}} \right) \left( \frac{n^{\text{r}}}{n^{\text{s}}} \right)^2}{I_{\text{f}}^{\text{r}}} \quad (1)$$

where r and s superscripts refer to the reference and sample respectively.  $I_{\text{f}}$  is the integrated area under the emission spectrum.  $A$  is the absorbance of solutions at the excitation wavelength, and  $(n^{\text{r}}/n^{\text{s}})^2$  stands for the refractive index correction. However, in this case, the aggregation effect is very strong and even for the highly diluted solutions employed for fluorescence measurements, the dimer concentration is not negligible with respect to that of the monomer. Thus, an additional correction had to be included, replacing  $(1-10^{-A})$ , the total absorbed light with the fraction of light absorbed by the monomer ( $\gamma_{\text{M}}$ ) in Eq. (1). This magnitude is defined by [13]:

$$\gamma_{\text{M}} = (1-10^{-A}) \frac{A_{\text{M}}}{A} \quad (2)$$

In order to evaluate  $\gamma_{\text{M}}$ , it was necessary to determine the monomer absorbance ( $A_{\text{M}}$ ) at 610 nm. This was achieved by fitting the absorption spectrum of 2 in the Q-band for the solution employed to calculate  $\Phi_{\text{f}}$ . Monomer ( $[\text{M}]$ ) and

dimer ( $[D]$ ) concentrations corresponding to this solution were found through an iterative method, based on the Lambert–Beer law, for all wavelengths, absorption coefficients, and the dimerization constant:

$$K_d = \frac{[D]}{[M]^2} \quad (3)$$

The experimental and calculated spectra are shown in Fig. 3.  $\Phi_F$  calculation was finally carried out according to the corrected equation:

$$\Phi_F = \Phi_F^0 \left( \frac{I_0}{I_0'} \right) \left( \frac{1 - 10^{-A'}}{\gamma_M} \right) \left( \frac{n^2}{n'^2} \right)^2 \quad (4)$$

### 2.6. Singlet molecular oxygen photoproduction

The quantum yield for singlet oxygen photosensitization by **2** was determined in  $D_2O$  air-saturated solutions by time-resolved near-IR phosphorescence detection [18,19]. Excitation was performed at 670 nm with a Spectron SL4000 Pyridine 1 dye laser pumped by a doubled Q-switched Spectron SL800 Nd:YAG laser (532 nm, pulsewidth 8 ns). The sample cuvette (fluorescence quartz cell,  $10 \times 10$  mm path-length) was placed in a home-made cell holder, and the luminescence was detected at a right angle by a biased Judson J16-8SP-R05M (5.00 mm diameter) Ge photodiode placed close to the cell. The emission passed through a Si-Glen Spectra filter (cut-off at 1050 nm, 2 mm thick) prior to detection. The detector output was amplified and fed to an optically-triggered Hewlett-Packard 54502A digitizing oscilloscope for recording. Signals were averaged to improve the signal-to-noise ratio, transmitted to a PC through an HPIB interface and stored for calculation. The excitation beam was attenuated by a neutral wedge. Pulse energies were measured using a home-built energy meter based on a Gentec ED-100S joulemeter and sent to the PC through an RS-232 interface.

$\Phi_\Delta$  was calculated by comparison of the emission with that of methylene blue as a reference compound ( $\Phi_\Delta = 0.55 \pm 0.03$  in  $D_2O$ ) [20].  $O_2$  ( $^1\Delta_g$ ) phosphorescence decays were fitted to a biexponential function by using the least squares non-linear Nelder–Meade algorithm. The fastest contribution was assigned to spurious light from the laser and, in the case of **2**, it also contained part of the phthalocyanine fluorescence. The amplitude of the term that contained the longest lifetime was taken as the phosphorescence intensity extrapolated to zero time ( $I_0$ ). The decays were recorded, for sample and reference, at various laser energies ( $E_i$ ). The slopes ( $S_\Delta$ ) were obtained from the linear plots of  $I_0$  versus  $E_i$ . Again, the correction for the fraction of light absorbed by the monomer had to be made, and the quantum yields were calculated using Eq. (5):

$$\Phi_\Delta = \Phi_\Delta^0 \left( \frac{S_\Delta}{S_\Delta'} \right) \left( \frac{1 - 10^{-A'}}{\gamma_M} \right) \quad (5)$$

## 3. Results and discussion

### 3.1. Synthesis

The available tetrakis (1,1-dimethyl-2-amino)ethyl-phthalocyaninato zinc (II) [14] **1** was employed as the starting material for the preparation of the cationic phthalocyanine **2**. This was achieved with high yields through exhaustive methylation [21], using the sterically hindered non-nucleophilic base diisopropylethylamine as a proton acceptor. Although disappearance of **1** was monitored by TLC, purification of the product by column chromatography is not possible since **2** is adsorbed in a non-reversible manner to conventional stationary phases such as silica, alumina, cellulose, and C-18 bound silica. Isolation of **2** from the reaction mixture was carried out by taking advantage of its insolubility in hydrophobic organic solvents.

$^1H$  NMR spectra of phthalocyanines often give broad signals due to aggregation and to short relaxation times [22,23]. In our case, the broadening of signals did not allow the obtention of information from the partition. Integration of signals agreed with the expected number of protons.

The FAB-MS showed a very weak signal at  $m/z$ : 1415 ( $M^+$ ) and a characteristic pattern between  $m/z$ : 989 and 600. The pattern begins with a peak at  $m/z$ : 989 that corresponds to the loss of three molecules of methyl iodide from the ion  $m/z$ : 1415 [24]. The base peak at  $m/z$ : 752 arises from the progressive expulsion of four molecules of trimethylamine from the ion  $m/z$ : 989 [25]. Intermediate peaks at  $m/z$ : 929, 869, and 811 were also observed. All the signals in the group were 15 mass units apart, corresponding to methyl elimination from the tert-butyl groups as well as methane expulsion from the quaternary ammonium group [25].

### 3.2. Dimerization

Phthalocyanine **2** is highly soluble in water but, all the same, strong aggregation is evidenced by deviations from the Lambert–Beer law. Its absorption spectrum in water shows an important dimer band at 630 nm even at low concentrations, as shown in Fig. 1. This situation is reverted when tetrahydrofuran (THF) is employed as a solvent: the monomer band at 680 nm is enhanced and the dimer absorption at 630 nm becomes negligible.

Dimerization of **2** in water was quantitatively evaluated in the 500–800 nm range (Q band) for solutions between  $1 \times 10^{-4}$  and  $7 \times 10^{-7}$  M. As concentration was raised, the absorption at 680 nm decreased while the band at 630 nm became higher, with an isosbestic point at 670 nm (see Fig. 2).

The calculated monomer and dimer spectra are plotted in Fig. 3 and the dimerization constant  $K_d$  is shown in Table 1. Its high value indicates that although the four positively charged quaternary ammonium groups give the dye a high solubility in water, the hydrophobic effect that arises from

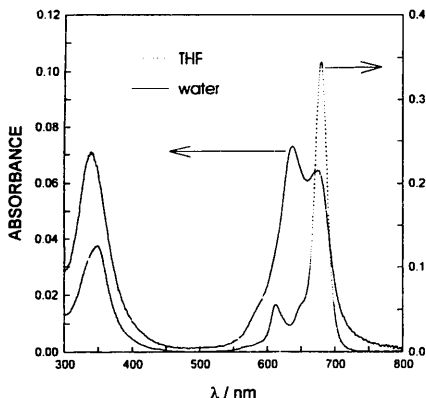


Fig. 1. Absorption spectra of **2** in water (—) and in THF (···). Concentration:  $10^{-6}$  M; pathlength: 1 cm.

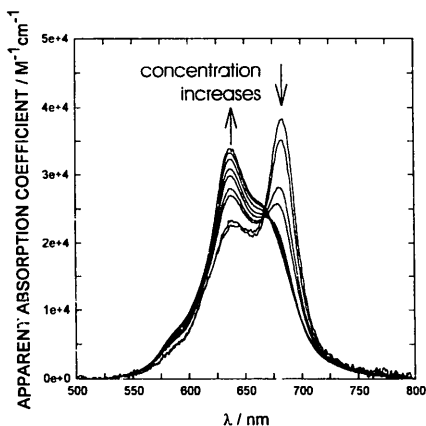


Fig. 2. Normalized absorption spectra of **2** in water at various concentrations:  $9.08 \times 10^{-6}$ ,  $6.81 \times 10^{-6}$ ,  $1.70 \times 10^{-5}$ ,  $1.14 \times 10^{-5}$ ,  $5.67 \times 10^{-6}$ ,  $3.78 \times 10^{-6}$ ,  $1.26 \times 10^{-6}$ ,  $1.05 \times 10^{-6}$ , and  $7.01 \times 10^{-7}$  M.

Table 1  
Photophysical parameters obtained for monomeric **2** in aqueous solutions

$\lambda_{max}$ (nm)	$\epsilon_{max}$ ( $M^{-1} cm^{-1}$ )	$K_d$ ( $M^{-1}$ )	$\Phi_1$	$\Phi_3$	$\Phi_f$	$\tau_1^{10}$ ( $\mu s$ )
685	$(9.5 \pm 0.8) \times 10^4$	$(2.1 \pm 0.3) \times 10^6$	$0.31 \pm 0.04$	$0.68 \pm 0.16^a$	$\approx 0.68^b$	$> 400^c$

<sup>a</sup> Average of the three measurements.

<sup>b</sup> Estimated from  $\Phi_3$  value.

<sup>c</sup> Estimated value (see text).

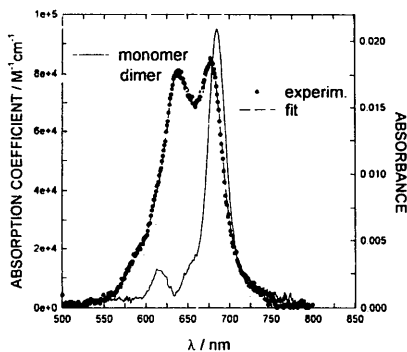


Fig. 3. Calculated monomer (—) and dimer (···) absorption spectra of **2** in water. Experimental (•••) and calculated (---) absorption spectra for the aqueous solution of **2** at a concentration of  $6.9 \times 10^{-7}$  M employed for  $\Phi_f$  calculation.

equilibrium towards dimer formation in aqueous solutions. A similar value of  $K_d$  has been reported for the anionic Zn (II) phthalocyanine tetrasulphonate (ZnTSPC) in the same medium [26].

The monomer spectrum is similar to that reported for different zinc phthalocyanines. On the other hand, the dimer is blue-shifted and is different from the corresponding spectra of other phthalocyanines of the same family previously studied in our laboratory [16]. This agrees with the fact that, while dimer spectra of metallated phthalocyanines are dependent on the peripheral substituents and solvent polarity, that of the monomer remains practically unchanged [27,28].

### 3.3. Fluorescence

The emission and excitation spectra of **2** in water are shown in Fig. 4. For the emission spectrum, an excitation wavelength of 610 nm was employed and, for the excitation spectrum, fluorescence was monitored at 710 nm. When excitation was performed in the Soret band (300–400 nm), the same emission spectrum was obtained.

The excitation spectrum is coincident with the absorption spectrum of the monomeric phthalocyanine (see Figs. 1 and 3). By comparison with Fig. 4, fluorescence can be attributed only to the monomer. The fluorescence quantum yield  $\Phi_f$

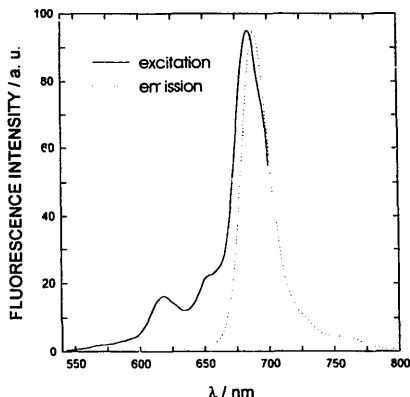


Fig. 4. Fluorescence ( $\lambda_{em} = 610$  nm) and fluorescence excitation ( $\lambda_{em} = 710$  nm) at a concentration of  $6.9 \times 10^{-7}$  M spectra of **2** in water.

(Table 1) has the typical value reported for other zinc phthalocyanines in different solvents [26,29–31].

### 3.4. Singlet molecular oxygen photoproduction

The  $O_2$  ( $^1\Delta_g$ ) production quantum yield,  $\Phi_\Delta$ , in deuterated water ( $D_2O$ ) was calculated at three different concentrations in order to obtain values at different monomer–dimer relative quantities. Upon correction in terms of the fraction of light absorbed by the monomer, Eq. (5), the values obtained were  $0.68 \pm 0.14$ ,  $0.67 \pm 0.13$ , and  $0.69 \pm 0.20$ . For the more diluted solution, the  $O_2$  ( $^1\Delta_g$ ) phosphorescence signal was very weak and, there was a poor correlation between  $I_\Delta$  and  $E_i$ . This consequently led to a greater deviation in the  $\Phi_\Delta$  value.

Assuming as a first approximation that  $\Phi_T + \Phi_\Delta \cong 1$ , it is possible to state that, like other zinc phthalocyanines [16], the triplet state of **2** completely deactivates itself via energy transfer to the dissolved oxygen [32,33]. This can be expressed by the efficiency  $S_\Delta$ :

$$S_\Delta = \frac{\Phi_\Delta}{\Phi_T} = \frac{k_{et}[O_2]}{k_{et}[O_2] + (1/\tau_T^0)} \cong 1 \quad (6)$$

where  $\Phi_T$  is the triplet quantum yield of **2**,  $k_{et}$  is the second order rate constant for the quenching of the triplet state of **2** by oxygen,  $[O_2]$  the oxygen concentration, and  $\tau_T^0$  the triplet lifetime of **2** in the absence of quencher. Assuming that  $k_{et}$  has a diffusional value [34], and that  $[O_2] = 0.265 \times 10^{-3}$  M at 25°C [35],  $\tau_T^0 > 400$   $\mu$ s can be estimated. Moreover,  $\Phi_T \cong 0.7$  agrees with results obtained for ZnTSPC by other authors [36].

## 4. Conclusions

The photophysical properties of this new cationic water-soluble phthalocyanine are similar to those of other Zn phthalocyanines. Substituents have no influence on excited state parameters. However, the aggregation effect depends on the substituents and the solvent. The Coulombic effect of the positively charged substituents is not enough to prevent aggregation.

## Acknowledgements

Funding for this research was provided by Universidad de Buenos Aires (UBACyT EX/154/95 and FA/136/95), Argentina, and GTZ (Gesellschaft für Technische Zusammenarbeit), Germany.

## References

- [1] M.T. Foutlier, V. Vonars-Coinsman, L. Morlet, I.X. de Brito, N. Robillard and T. Patrice, Photodynamic therapy of cancers, in G. Jori, R.H. Potter, M.A.J. Rodgers and T.G. Truscott (eds.), *Photobiology in Medicine*, Plenum Press, New York, 1994, pp. 177.
- [2] J.D. Spikes, Phthalocyanines as photosensitizers in biological systems and for the photodynamic therapy of tumors, *Photochem. Photobiol.* 43 (1986) 691–699.
- [3] I. Rosenthal, Phthalocyanines as Photodynamic Sensitizers, *Photochem. Photobiol.* 53 (1991) 859–870.
- [4] B. Paquette and J.E. van Lier, Phthalocyanines and related compounds: Structure-activity relationship, in B.W. Henderson and T.J. Dougherty (eds.), *Photodynamic Therapy*, Marcel Dekker, New York, 1992, pp. 145.
- [5] T.S. Mang, C. Meginnis, C. Liebow, F.O. Nseyo, D.H. Crean and T. Dougherty, Fluorescence detection of tumors—early diagnosis of microscopic lesions in preclinical studies, *Cancer* 71 (1993) 269–272.
- [6] A. Ruck, G. Beck, R. Bachor, N. Akgun, M.H. Gschwend and R. Steiner, Dynamic fluorescence changes during photodynamic therapy in vivo and in vitro of hydrophilic Al(III) phthalocyanine tetrasulphonate and lipophilic Zn(II) phthalocyanine administered in liposomes, *J. Photochem. Photobiol. B: Biol.* 36 (1996) 127–134.
- [7] R.W. Boyle and D. Dolphin, Structure and biodistribution relationships of photodynamic sensitizers, *Photochem. Photobiol.* 64 (1996) 469–485.
- [8] A. Villanueva, The cationic meso-substituted porphyrins: An interesting group of photosensitizers, *J. Photochem. Photobiol. B: Biol.* 18 (1993) 295–296.
- [9] M. Merchat, G. Bertolini, P. Giacomini, A. Villanueva and G. Jori, Meso-substituted cationic porphyrins as efficient photosensitizers of Gram-positive and Gram-negative bacteria, *J. Photochem. Photobiol. B: Biol.* 32 (1996) 153–157.
- [10] D. Wührle, J. Gitzel, I. Okura and S. Aono, Photoredox properties of tetra-2,3-pyridinoporphyrazines (29H,31H-tetrapyrrodo[2,3-b:2',3'-g:2'',3''-4'',2'',3''-q]-porphyrazine), *J. Chem. Soc., Perkin Trans. 2* (1985) 1171–1178.
- [11] A.K. Sobbi, D. Wührle and D. Schlettwein, Photochemical stability of various porphyrins in solution as thin film electrodes, *J. Chem. Soc., Perkin Trans. 2*, (1993) 481–494.
- [12] D.D. Perrin and W.L.F. Armarego, *Purification of Laboratory Chemicals*, Pergamon Press, Oxford Third edition, 1988.
- [13] R.M. Negri, A. Zalts, E.A. San Román, P.F. Aramendia and S.E.

- Braslavsky, Carboxylated Zinc Phthalocyanine: influence of dimerization on the spectroscopic properties. An absorption, emission and thermal lensing study. *Photochem. Photobiol.* 53 (1991) 317–322.
- [14] D.A. Fernández, L.E. Diccio and J. Awruch, Synthesis and properties of two new N-alkyl-substituted phthalocyanines. *J. Heterocycl. Chem.* 32 (1995) 519–522.
- [15] M. Kubista, R. Sjöback and B. Albinsson, Determination of equilibrium constants by chemometric analysis of spectroscopic data. *Anal. Chem.* 65 (1993) 994–998.
- [16] D.A. Fernández, J. Awruch and L.E. Diccio, Photophysical and Aggregation Studies of *t*-Butyl-Substituted Phthalocyanines. *Photochem. Photobiol.* 63 (1996) 784–792.
- [17] C.A. Parker, *Photoluminescence of Solutions*, Elsevier, Amsterdam, 1968.
- [18] S. Nonell i Marrugat, Ph.D. Thesis, Max-Planck-Institut für Strahlenchemie Mülheim/Ruhr, 1988.
- [19] P.F. Aramendía, R.W. Redmond, S. Nonell, W. Schuster, S.E. Braslavsky, K. Schaffner and E. Vogel, Photophysical properties of porphycenes: Potential photodynamic therapy agents. *Photochem. Photobiol.* 44 (1986) 555–559.
- [20] F. Wilkinson, W.P. Helman and A.B. Ross, Quantum yields for the photosensitized formation of the lowest electronically excited singlet state of molecular oxygen in solution. *J. Phys. Chem. Ref. Data* 22 (1993) 113–262.
- [21] H.Z. Sommer, H.I. Lipp and L.L. Jackson, Alkylation of amines. A general exhaustive alkylation method for the synthesis of quaternary ammonium compounds. *J. Org. Chem.* 36 (1971) 824–828.
- [22] P. Haisch and M. Hanack, Synthesis of unsymmetrically-substituted Nickel, Palladium and Platinum phthalocyanines. *Synthesis* (1995) 1251–1256.
- [23] M. Sommerauer, C. Rager and M. Hanack, Separation of 2(3), 9(10), 16(17), 23(24) tetrasubstituted phthalocyanines with newly developed HPLC phases. *J. Am. Chem. Soc.* 118 (1996) 10085–10093.
- [24] E. Baranowska, R. Ostaszewski, J. Jurczak, R.H. Fokkens and N.M.M. Nibbering, Fast atom bombardment mass spectra of some N,N'-tetramethyl diazacoronands diiodides. *Org. Mass Spectrom.* 24 (1989) 431–434.
- [25] K.G. Furton and C.F. Poole, Fast atom bombardment mass spectra of some tetra-*n*-butylammonium salts. *Org. Mass Spectrom.* 22 (1987) 377–378.
- [26] A. Harriman and M. Richoux, Attempted photoproduction of hydrogen using sulphophthalocyanines as chromophores for three-components systems. *J. Chem. Soc. Faraday Trans.* 2, 76 (1980) 1618–1626.
- [27] M.J. Stillman and T. Nyokong, Absorption and magnetic circular dichroism spectral properties of phthalocyanines Part I: Complexes of the dianion  $Pe(-2)$ , in C.C. Leznoff and A.B.P. Lever (eds.), *Phthalocyanines: Properties and Applications*, VCH, New York, 1989, pp. 133–289.
- [28] M.G. Lagorio, L.E. Diccio and E.A. San Román, Visible and near-IR spectroscopic and photochemical characterization of substituted metallo-phthalocyanines. *J. Photochem. Photobiol. A: Chem.* 72 (1993) 153–161.
- [29] J.A. Darwent, P. Douglas, A. Harriman, G. Porter and M. Richoux, Metal phthalocyanines and porphyrins as photosensitizers for reduction of water to hydrogen. *Coord. Chem. Rev.* 44 (1982) 83–126.
- [30] T. Shen, Z. Yuan and H. Xu, Fluorescent properties of phthalocyanines. *Dyes and Pigments* 11 (1989) 77–80.
- [31] T. Zhang and H. Xu, Influence of halogenation and aggregation on photosensitizing properties of zinc phthalocyanine (ZnPC). *J. Chem. Soc. Faraday Trans.* 89 (1993) 3347–3351.
- [32] B.D. Richter, M.E. Kenney, W.E. Ford and M.A. Rodgers, Synthesis and photoproperties of diamagnetic octabutoxyphthalocyanines with deep red optical absorbance. *J. Am. Chem. Soc.* 112 (1990) 8064–8070.
- [33] M.E. Daraio, P.F. Aramendía, E.A. San Román and S.E. Braslavsky, Carboxylated zinc-phthalocyanines-II. Dimerization and singlet molecular oxygen sensitization in hexadecyltrimethylammonium bromide micelles. *Photochem. Photobiol.* 54 (1991) 367–373.
- [34] A.U. Kahn, The discovery of the chemical evolution of singlet oxygen. Some current chemical, photochemical, and biological applications. *Int. J. Quantum Chem.* 39 (1991) 251–267.
- [35] S.L. Murov, *Handbook of Photochemistry*, Marcel Dekker Inc., New York, 1973.
- [36] J.R. Darwent, I. McCubbin and G. Porter, Photo-reduction of methyl viologen sensitized by sulphamated phthalocyanines in micellar solutions. *J. Chem. Soc. Faraday Trans.* 2, 78 (1982) 903–910.