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Novel Synthetic Cycloketo-Tetraphenylporphyrins

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New tetraphenylporphyrins **2a** and **2b** have been synthesized and characterized. Both compounds possess an ethanone bridge that connects the porphyrin ring with one of the phenyl groups at the periphery. Tetraphenylporphyrin **2a** also has a methyl group on the same phenyl ring, whereas tetraphenylporphyrin **2b** lacks this substituent. This small difference results in **2a** and **2b** having markedly different photophysical properties. In particular, **2a** proved to be a highly efficient sensitizer for singlet oxygen generation with a quantum yield of 0.85. A reference compound **2c** has also been synthesized in which the porphyrin ring is connected to one of the peripheral phenyl groups through just a keto function. Thus, the effect of the size of the exocyclic ring on conjugation and photophysical properties has been studied.

Introduction

Many porphyrins and analogous structures are currently under intense investigation as they exhibit remarkable properties that can be exploited in the fields of material science, medicine, biochemistry or optoelectronics.[1] With regard to medical applications, the photodynamic therapy (PDT) of tumours represents the most prominent and successful transfer from basic to applied science in the porphyrin field.[2] Since the beginning of the 20th century, many scientists have searched for substances able to take advantage of light energy for several medical applications. Based on the pioneering work of Tappeiner and Jesionek,[3] modern PDT has been developed and has flourished, especially since the 1970s (the work of Dougherty et al.).[4] The crucial point in PDT is the utilization of an effective photosensitizer that is able to accumulate in malignant tissue and cause the so-called photodynamic effect. It comprises the absorption of light of a specific wavelength leading to excitation of the sensitizer to an electronically excited triplet state (T_1) by ISC from the excited singlet state (S_1). In its T_1 state the sensitizer molecule can undergo several reactions of which, under normal physiological conditions, the most predominant is the Type II photoreaction. Thereby energy is transferred from the sensitizer to the triplet molecular oxygen ($^3O_2$) to produce highly reactive singlet oxygen ($^1O_2$) which is believed to be the most important cytotoxic species.[5] Although a sensitizer's biodistribution and its ability to target tumours are pressing problems in PDT, a high singlet oxygen quantum yield is still considered a fundamental requirement for successful treatment. Up to now many approaches have been followed to develop highly effective photosensitizers, but many of them lack outstanding photophysical properties. Sensitizers that have formerly been used, most of them porphyrins or porphyrinoids,[6] often suffer from additional problems, for example, they have a long half-life in patients' skin or eyes leading to high light-sensitivity, pain associated during PDT treatment or difficulties in synthesis and/or purification.[7] This led us to attempt to synthesize simple, fully synthetically accessible compounds that have a defined structure and furthermore are as effective as possible in photobiophysical applications like PDT.

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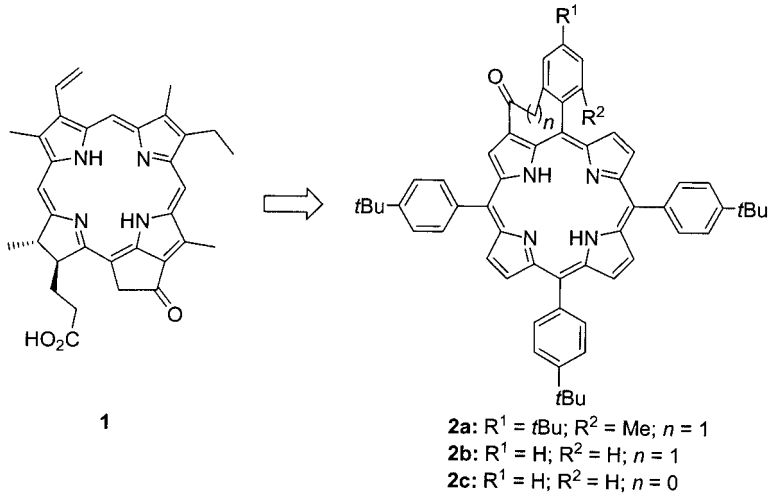
Choosing a Target

Based on the knowledge gained from studies on pyropheophorbide *a* (**1**)[8] and its derivatives we were looking for characteristics to be incorporated into a synthetic porphyrin to form a potential photosensitizer which would hopefully help in overcoming known disadvantages like unfavourable stability and laborious preparation protocols. As a consequence, a suitable system should have low symmetry, an exocyclic ketone moiety connecting a meso substituent with the proximate β-pyrrolic position on the macrocycle and a preserved porphyrin structure without the formation of a partially reduced system to grant higher stability. We chose our recently developed monofunctionalized porphyrin building block,[9] being easily accessible and also easily converted into the target **2a** which fulfils the above-mentioned criteria. For comparative studies we furthermore chose two reference systems: one simpler model bearing the same exocycle, **2b**, and a model with a six-membered exocy-



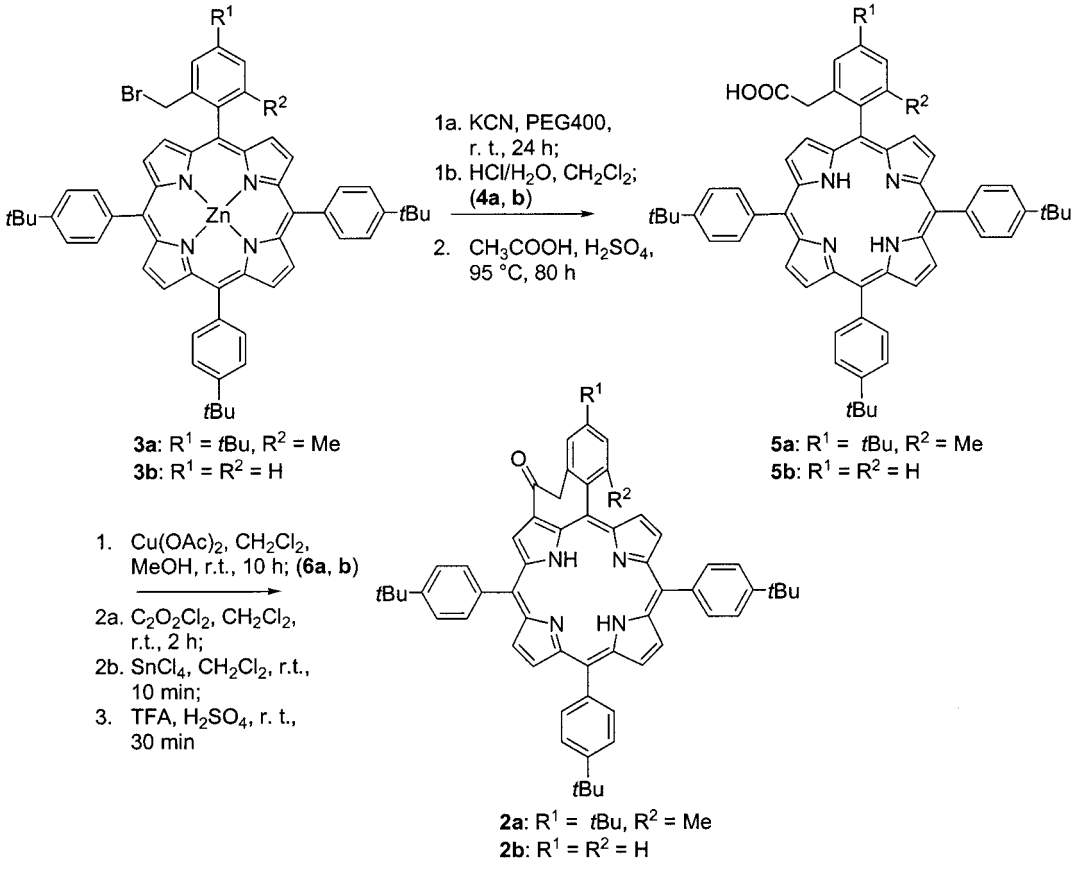
Scheme 1. Adoption of characteristics of **1** in the synthetic model **2a**; porphyrins **2a**–**c** are racemic mixtures as a result of atropisomerism.

cle, **2c** (Scheme 1), in analogy to systems already reported by Callot and co-workers.[10]

Results and Discussion

Synthetic Access to 2a–c

As direct carboxylation of the zinc(II) complex of the *o*-bromomethyl-substituted building block **3a** through bromine–lithium exchange or conversion into a Grignard reagent was unsuccessful, we first replaced the bromide by cyanide to give the corresponding cyanomethylzinc(II) porphyrin. The zinc(II) ion in the bromomethylporphyrin precursor **3a** proved to be essential under the applied reaction conditions (KCN, PEG 400) owing to better solubility and the strong nitrile–zinc ion interaction increasing the local cyanide concentration close to the substitution site. This interaction is also believed to encourage oligomer formation



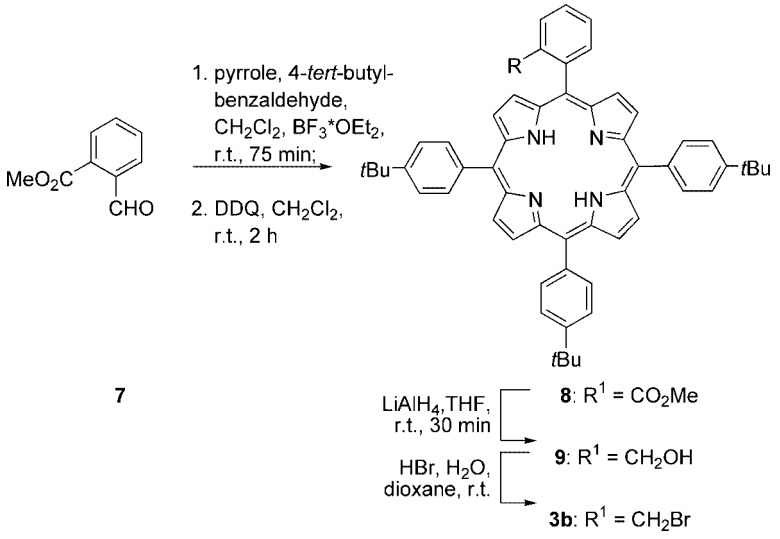
Scheme 2. Synthesis of **2a** and **2b**; PEG 400: poly(ethylene glycol) 400; **2a** and **2b** are racemic mixtures.

which makes the characterization of the cyanomethylzinc(II) porphyrin rather tedious. Hence, it was directly demetallated to give the cyano-porphyrin **4a** in excellent yield, which was fully characterized. The acidic hydrolysis of nitrile **4a** under forced conditions (acetic acid, sulfuric acid, water, 95 °C, 80 h) led to the porphyrinethanoic acid **5a** (Scheme 2).

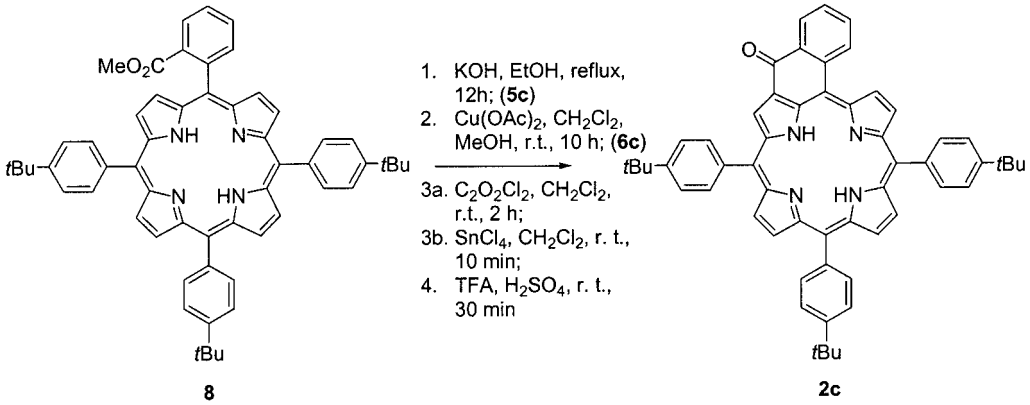
To prevent protonation in the next steps, the moderately acid-stable copper(II) complex **6a** was prepared but not purified and directly converted into its acid chloride which was immediately subjected to a Friedel–Crafts acylation protocol. Thus, the exocyclic ketone moiety was established. Because partial loss of the copper(II) ion was observed, it was completely removed with a strongly acidic mixture consisting of TFA and sulfuric acid. The free base keto-porphyrin **2a** (Scheme 2) was obtained in an overall yield of 59% (based on **5a**) as a racemic mixture of two C_1-symmetrical species. Because rotation around the C–C bond between the porphyrin and annelated phenyl ring in **2a** was no longer possible, stable atropisomers possessing axial chirality were generated.

To further investigate the structure–property relationship of **2a**, we synthesized **2b** and **2c** starting from the easily accessible methyl 2-formylbenzoate[11] (**7**). Condensation with 4-*tert*-butylbenzaldehyde and pyrrole under BF_3–diethyl ether catalysis furnished **8** directly in more than 17% yield. The ester group of **8** was reduced to the alcohol **9** which was immediately treated with a solution of hydrogen bromide in glacial acetic acid to give the bromomethylporphyrin **3b** (Scheme 3). This porphyrin resembles **3a** but lacks the *o*-methyl and one of the *tert*-butyl substituents. Porphyrin **2b** was then synthesized following exactly the strategy described above for the synthesis of **2a**. After this procedure, **2b** was isolated as a racemic mixture in 65% yield (based on **5b**). Again, as was observed for **2a**, stable atropisomers were generated as a result of hindered rotation (C_1 symmetry).

The second reference system, **2c**, the Callot-like model,[10] was obtained by basic saponification of **8** using powdered KOH in ethanol (12 h, reflux), giving the free acid **5c**. Subsequently, porphyrin **2c** was synthesized following the same procedures as described above for the conversion of **5a** into **2a** (Scheme 4). Thus, **2c** was obtained via the copper(II) porphyrin, the acid chloride and the corresponding copper(II) keto-porphyrin in a comparable yield (61% based on **5c**), as described by Callot and co-workers.[10]



Scheme 3. Synthethis of bromomethylporphyrin **3b**, the precursor of **2b** (racemic mixture).



Scheme 4. Synthethis of the reference system **2c**.

NMR Studies

The ^{1}H NMR spectra of **2a** and **2b** show several characteristic features of chiral C_1 symmetric compounds. The diastereotopic protons of the ethano bridges connecting one of the meso-phenyl rings to the porphyrin macrocycle appear between δ = 4 and 6 ppm as two doublets with geminal couplings constants of 11.5 (**2a**) and 11.9 Hz (**2b**), respectively. These can be used to monitor the thermal stability of the configurations of **2a** and **2b** towards inversion processes of the seven-membered ring, potentially leading to racemization. Temperature-dependent NMR spectra recorded in $C_2D_2Cl_4$ covering a temperature range of 20–110 °C for both **2a** and **2b** do not show even the beginning of coalescence, proving the configurational stability at room temperature and also at elevated temperatures. For **2a**, the protons of the substituted phenyl ring give rise to two signals at δ = 7.35 and 7.68 ppm with a ^4J value of 1.7 Hz. The resonances for the aromatic protons of the non-modified meso substituents appear in the region of 7–8.4 ppm. Some of these signals are significantly broadened as a result of rotational processes while others give well-defined doublets. Owing to the unsymmetrical nature of **2a**, the pyrrolic protons give rise to a singlet at δ = 8.96 ppm for the proton next to the annelated ring and to three pairs of doublets between 8.63 and 8.89 ppm with geminal coupling constants of around 4.7 Hz. The signals for the inner NH proton resonances appear at around –1.7 ppm, that is, in the same region as those in **1**, being significantly shifted downfield by nearly 1 ppm relative to non-cyclized precursors. In contrast, the Callot-like reference system **2c** shows important differences. Whereas the splitting of the resonances arising from the pyrrolic protons is analogous, the signals for the phenylic protons appear as two sharp sets of doublets in a 1:1 ratio at around 7.7 and 8.0 ppm. Evidently, rotation of the *tert*-butylphenyl rings is comparable to that observed for other meso-tetraphenyl-substituted porphyrins,[12] resulting in three pseudo-AB spin systems. On the NMR timescale, the upper and lower halves of the porphyrin system in **2c** seem to be identical. From this it can be concluded that the potential atropisomers in **2c** are not stable but interchange quickly. Furthermore the NH resonance is found at –0.55 ppm, representing a huge downfield shift of around 2.2 ppm relative to the non-cyclized precursor **8**. Thus, the phenyl ring bearing the keto linker affects the electron density of the porphyrin macrocycle owing to extensive conjugation (see the calculated structure models in Figure 2).

Cyclic Voltammetry

All systems bearing exocyclic ketone moieties show strong shifts of the half-wave potentials to positive potentials in the cathodic region compared with a non-annelated reference system **10**, that is, 5^4,10^4,15^4,20^4-tetra-*tert*-butyl-5^2-methoxymethyl-5^6-methyl-5,10,15,20-tetraphenylporphyrin.[9] In Figure 1, the half-wave potentials for reference compound **10**, which is the direct precursor of **3a**,[9] are displayed as dashed lines. The exact potential values are given in Table 1. Evidently, **2a** is more difficult to reduce than **2b** or **2c**. It is reasonable to assume that this is due to the better conjugation of the modified phenyl ring with the porphyrin and the keto functionality in **2c** (see also Figure 2). In **2a**, only the carbonyl group can interact with the porphyrin which makes electron uptake more difficult. With **2b**, an irreversible process is visible in the cathodic region, whose origins are so far not understood. The potentials of **2a**–**2c** in the anodic region resemble more or less those of reference porphyrin **10**.

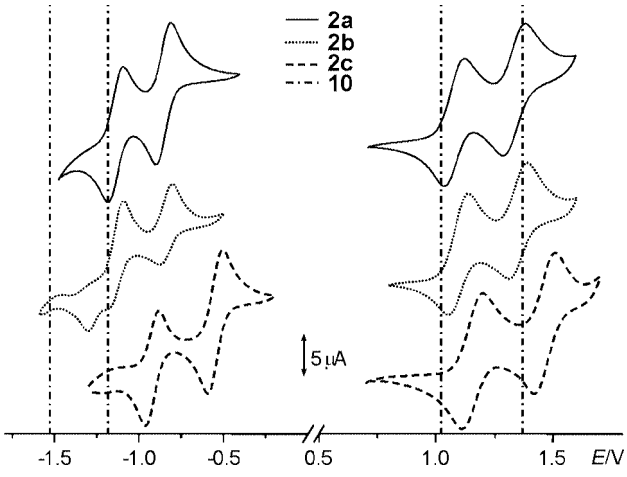


Figure 1. Cyclic voltammetry of **2a**–**c** ($c = 1.0 \times 10^{-3}$ M) in CH_2Cl_2 (nBu$_4$NPF$_6$ as the supporting electrolyte at c = 0.1 M) at 25 °C; gold disc electrode (0.07 cm^2); counter electrode: platinum wire; reference electrode: Ag/AgCl (3 M NaCl); scan rate: v = 50 mV s^{-1}; Potentials are given versus ferrocene with E(Fc/Fc$^+$) = +0.53 V as the internal standard. The vertical dashed lines show the positions of the half-wave potentials for a simple precursor porphyrin **10**.

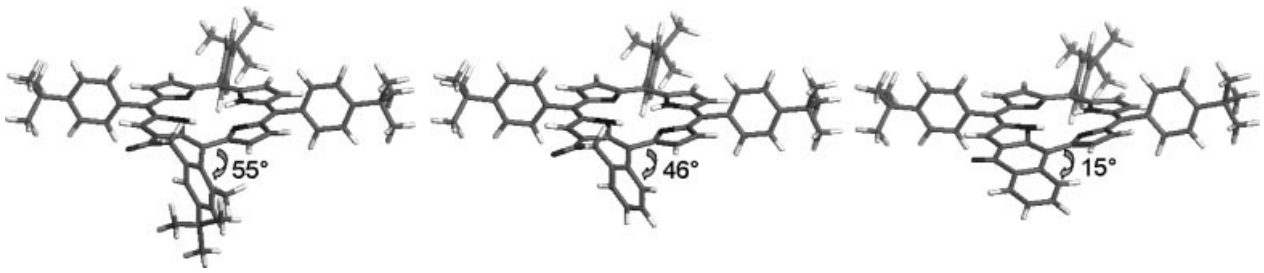


Figure 2. Calculated structures (at the PM3 level) of the cycloketo-porphyrins **2a**–**c**.[13] Arrows and degree values represent the dihedral angle between the C_{meso}–C_α bond of the porphyrin and the plane of the *meso*-phenyl substituent.

Table 1. Half-wave potentials, $E_{1/2}$, of **2a**–**c** and **10** in CH_2Cl_2. Potentials are given versus ferrocene with $E(Fc/Fc^+)$ = +0.53 V as the internal standard.

Compound	$E_{1/2}^{Red2}$ [V]	$E_{1/2}^{Red1}$ [V]	$E_{1/2}^{Ox1}$ [V]	$E_{1/2}^{Ox2}$ [V]
2a	–1.23	–0.95	+1.02	+1.25
2b	–1.20	–0.84	+1.10	+1.35
2c	–1.01	–0.63	+1.07	+1.38
10	–1.53	–1.19	+1.02	+1.38

PM3 Calculations

PM3-minimized structures[13] of the keto-porphyrins **2a**–**2c** are shown in Figure 2. As can clearly be seen, all compounds are non-planar with various degrees of deviation from planarity. The *ortho* substituent on the opposite site of the ketone-bearing addend gives rise to sterically unfavourable interactions with the closest β-pyrrolic hydrogen atom. As an indication of the strength of these hindrances, we calculated the dihedral angle between the C_{meso}–C_α bond and the plane of the meso-phenyl substituent. For **2b** and **2c**, which carry a hydrogen atom in this *ortho* position, the interactions are, as expected, smaller than in **2a**. The dihedral angle is rather small in **2c**, about 15°, but increases to 46° in **2b**. Because of the C_2 bridge in **2b**, the phenyl ring is not forced into the porphyrin plane and therefore the phenyl ring is more tilted than is usually observed in tetraphenylporphyrins. With the large methyl group of **2a**, the steric hindrance becomes very pronounced and the dihedral angle rises to 55°, although it is not as large as one would expect. It seems that the non-planarity of the porphyrins **2a**–**c** is modulated by two opposing effects: 1) the steric hindrance of the *ortho* groups, which increases the strain, and 2) the length of the bridge that tilts the phenyl ring with respect to the porphyrin plane.

Interestingly, comparison of the frontier orbitals of porphyrins **2a**–**c** clearly shows that in **2c** the six-membered keto ring is part of the porphyrin′s π system (Figure 3). This is not possible for **2a** and **2b** because the CH_2 unit does not support conjugation. Nevertheless, for all keto systems a pronounced participation of the keto group as well as of the substituted phenyl ring is visible, which explains the red shift of the absorption bands of all the keto-porphyrins when compared with unmodified tetraphenylporphyrins such as the precursors **3a** or **8**.

Photophysical Properties

The UV/Vis absorption spectra of **2a**, **2b** and **2c** in DMF are presented in Figure 4, and the corresponding data are given in Table 2. The shapes of the absorption spectra are similar to those of metal-free porphyrins, consisting of a Soret band located in the blue region and the split Q-bands. The absorption spectrum of **2b** looks like that of **2a**, with minor differences (within 1–2 nm) in the positions of the absorption bands. The Soret band of **2c** is bathochromically shifted by 1100 and 1200 cm^{-1} (13.5 and 15.5 nm) relative to its position in the spectra of **2a** and **2b**, respectively. Sim-

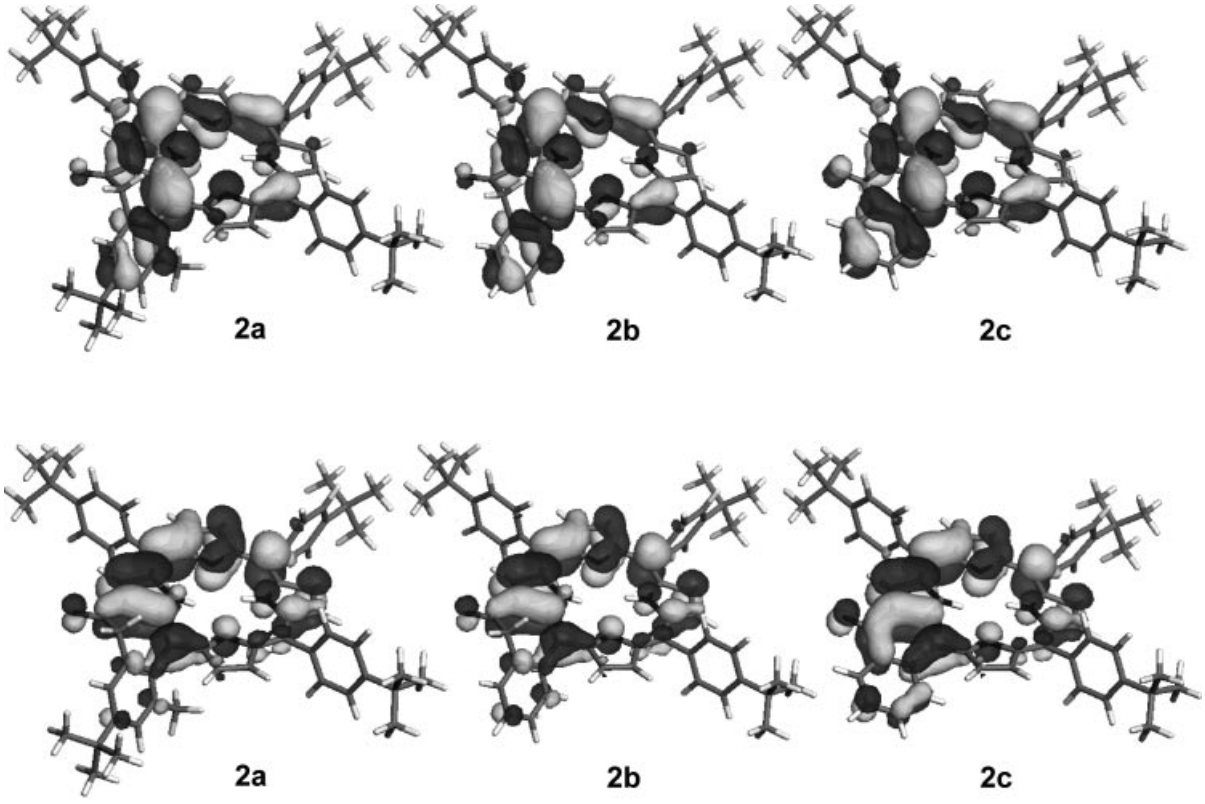


Figure 3. Top line: calculated shapes (Materials Studio®[13]) of the HOMOs of compounds **2a**–**c**. Bottom line: calculated shapes (Materials Studio®[13]) of the LUMOs of compounds **2a**–**c**.

Table 2. Absorption and fluorescence bands of **2a**–**c** in DMF.

Compound	Soret [nm]	Q_I [nm]	Q_{II} [nm]	Q_{III} [nm]	λ_{fl}[b] [nm]	Stokes shift [cm^{-1}]
2a	441.5 (22650)	543.5 (18400)	588.0 (17000)	689.0 (14500)	708.5 (14100)	400
2b	439.5 (22750)	542.0 (18450)	586.5 (17050)	687.5 (14550)	701.0 (14260)	290
2c	464.0 (21550)	577.0 (17330)	641.0 (15600)	744.5 (13430)	778.0 (12850)	580

[a] Values in parentheses are given in cm^{-1}. [b] Maximum of the fluorescence spectrum at excitation wavelength λ_{exc} = 532 nm.

ilar spectral shifts were also observed for the Q-bands (see Table 2). This result is not surprising if one takes into account the extended π-electron system of **2c** (see Figure 3 and the discussion above). Moreover, the fact that the Soret and Q-bands of **2c** have practically identical bathochromic shifts indicates that the extension of the π-electron system results in similar perturbations of the first and higher excited singlet states of this compound.

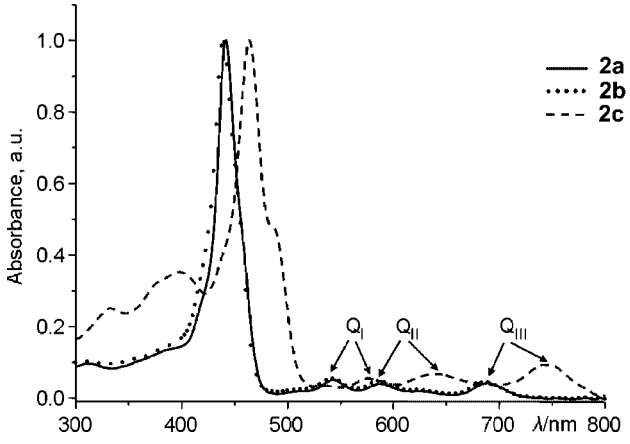


Figure 4. Steady-state absorption spectra of **2a** (solid), **2b** (dots) and **2c** (dashed) in DMF.

The steady-state fluorescence spectra of the compounds under investigation were recorded using an excitation wavelength of 532 nm (Figure 5). The maximum of the fluorescence spectrum of **2a** lies at 708.5 nm, whereas it was observed at 701 nm for **2b**, but the shapes and bandwidths of both spectra are similar. The Stokes shift between the maxima of the lowest energetic absorption and the fluorescence band is higher for **2a** than for **2b** (400 and 290 cm^{-1}, respectively; see Table 2).

The maximum of the emission spectrum of **2c** is red-shifted by 70 nm (1250 cm^{-1}) with respect to that of **2a** (Figure 4 and Table 2) and this value correlates well with that of the absorption spectra. Moreover, the shape of the fluorescence spectrum of **2c** is slightly broader than the fluorescence spectra of **2a** and **2b** (FWHM = 1450 cm^{-1} for **2c**, and 1210 and 1230 cm^{-1} for **2a** and **2b**, respectively). The fluorescence quantum yield (Φ_{fl}) for all three compounds is low, but for **2c** it is practically twice that of **2a** and **2b** (0.05 and 0.03, see Table 3).

As was mentioned above, photosensitized singlet oxygen generation is one of the important parameters used to determine whether a photosensitizer is suitable for PDT. It is

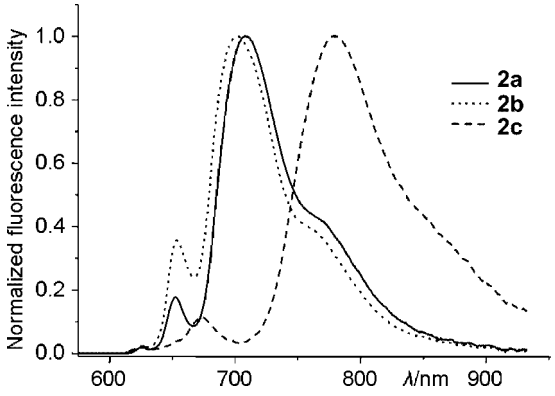


Figure 5. Fluorescence spectra of **2a** (black line), **2b** (dots) and **2c** (dashed) in DMF; λ_{exc} = 532 nm.

Table 3. Quantum yields for the fluorescence (Φ_{fl}), intersystem crossing $S_1 \rightarrow T_1$ (Φ_{ISC}) and photosensitized singlet oxygen (Φ_{Δ}) of **2a**, **2b** and **2c** in DMF.

Compound	Φ_{fl}	Φ_{ISC}	Φ_{Δ}
2a	0.03 ± 0.005	0.88 ± 0.05	0.85 ± 0.05
2b	0.03 ± 0.005	0.75 ± 0.05	0.65 ± 0.05
2c	0.05 ± 0.005	0.23 ± 0.05	0.22 ± 0.05

well-known that singlet oxygen ($^1O_2$, $^1\Delta_g$) is generated by energy transfer from the excited triplet state of a sensitizer molecule to molecular oxygen in its triplet ground state ($^3O_2$, $^3\Sigma_g^-$). Since the $^1O_2$ state lies 0.98 eV above the triplet ground state, the energy difference between T_1 and S_0 of a sensitizer should be above or around this value to allow the generation of singlet oxygen.[14,15] This prerequisite holds for 5,10,15,20-tetraphenylporphyrins with a triplet energy E_T of around 1.59 eV and phthalocyanines with an E_T value of around 1.2 eV.[16]

The singlet oxygen quantum yields, Φ_{Δ}, of **2a**, **2b** and **2c** were determined by steady-state measurement of the photosensitized singlet oxygen luminescence around 1270 nm.[17,18] For **2a** the singlet oxygen quantum yield has an extremely high value of 0.85, whereas for **2b** and **2c** it was determined to be 0.65 and 0.22, respectively. Comparing the corresponding values for singlet oxygen generation and the intersystem crossing (ISC) quantum yield, Φ_{ISC} (determined by picosecond transient-absorption spectroscopy), the efficiency of energy transfer $T_1 \rightarrow {}^3O_2$ could be estimated to be close to 1 for **2a** and **2c** and 0.9 for **2b** (see Table 3). The low values for ISC and photosensitized singlet oxygen generation of **2c** could be explained by the decrease

in the HOMO–LUMO gap and a more extended vibrational structure, thus increasing the probability of the first excited singlet state decaying directly to the ground state.

Conclusions

In this contribution we have presented the synthesis and characterization of the new keto-porphyrins **2a** and **2b**. To understand their photochemical and photophysical behaviour we also prepared the reference compound **2c** which resembles the well-known Callot-type keto-porphyrin systems. Interestingly, keto-porphyrin **2a** showed a remarkably high efficiency in the generation of singlet oxygen, having a quantum yield of Φ_Δ = 0.85. The absorption of **2a** at 689 nm is interesting and is more red-shifted than is typically observed with unsubstituted tetraphenylporphyrins, although not red-shifted as much as hoped for. The synthesis of these porphyrins with modified substitution patterns is currently being explored in an attempt to gain access to higher substituted systems. Owing to their potential application as sensitizers for singlet oxygen, the synthesis of water-soluble derivatives of **2a** deserves particular attention.

Experimental Section

General Remarks: All reactions were performed under nitrogen using distilled solvents. Dichloromethane was distilled from $LiAlH_4$, methanol from Mg and pyrrole from CaH_2. Other chemicals were purchased from Sigma–Aldrich, Acros Organics and Merck and used without further purification. Flash column chromatography (FC): silica gel 60 (ICN, 230–400 mesh). Thin-layer chromatography (TLC): silica gel 60 F_{254} on aluminium foil (Merck), visualization with UV light. Eluents for FC and TLC were distilled from K_2CO_3. Mass spectrometry (MS): Micromass Zabspec, FAB+ mode, 3-nitrobenzyl alcohol as matrix. NMR spectroscopy: JEOL EX 400, JEOL JNM 400, Bruker Avance 300, Bruker Avance 400; chemical shifts given in ppm; deuteriated solvent: $CDCl_3$ (also as internal standard: δ^1H = 7.24 ppm; $\delta^{13}C$ = 77.0 ppm) unless otherwise stated; all spectra were recorded at room temperature. IR spectroscopy: ASI React IR 1000, Analytical Services Inc. UV/Vis spectroscopy: Shimadzu UV-3102 PC UV/Vis/NIR Scanning Spectrophotometer. Elemental Analysis (EA): CE Instruments EA 1110 CHNS. Cyclic voltammetry measurements were performed on an Autolab Instrument with PGSTAT 30 in a three electrode arrangement (Deutsche Metrohm GmbH & Co. KG); measuring electrode: gold disc electrode (0.07 cm^2); counter electrode: Pt wire; reference electrode: Ag/AgCl (3 M NaCl); voltammograms were recorded at 25 °C in solution (solvent CH_2Cl_2) at sample concentrations of $c = 1.0 \times 10^{-3}$ M with the addition of n-Bu_4NPF_6 as electrolyte at c = 0.1 M and scan rates of v = 50 mV s^{-1}. Potentials are given versus ferrocene with $E(Fc/Fc^+)$ = +0.53 V as the internal standard. Absorption and steady-state fluorescence spectroscopy: The ground-state absorption spectra were recorded using a commercial Shimadzu UV-2501PC spectrophotometer at room temperature. Steady-state fluorescence spectra were measured in 1 cm × 1 cm quartz cells using a combination of a cw-Xenon lamp (XBO 150) and a monochromator (Lot-Oriel, bandwidth 10 nm) for excitation and a polychromator with a cooled CCD matrix as a detector system (Lot-Oriel, Instaspec IV).[19] To obtain fluorescence quantum yields, a solution of H_2TPP in DMF was used as standard (Φ_{fl} = 0.11).[20] Picosecond transient absorption spectroscopy (ps-TAS): To measure transient absorption spectra and determine the ISC quantum yield, a white light continuum was generated as a test beam in a cell containing D_2O/H_2O using intense 25 ps pulses from a Nd^{3+}:YAG laser (PL 2143A, Ekspla) at 1064 nm. Before passing through the sample, the continuum radiation was split to obtain a reference spectrum. The transmitted as well as the reference beams were focused into two optical fibers and were recorded simultaneously at different traces on a CCD matrix (Lot-Oriel, Instaspec IV). Tunable radiation from an OPO/OPG (Ekspla PG 401/SH, tuning range 200–2300 nm), pumped by the third harmonic of the same laser, was used as an excitation beam. The mechanical delay line allowed the measurement of light-induced changes of the absorption spectrum at different delays of up to 15 ns after excitation. The optical density of all samples was 1.0 at the maximum of absorption Q-band. The analysis of experimental data was performed using the compensation method.[21] Photosensitized steady-state singlet oxygen luminescence was measured at 1270 nm. A cw Yb:YAG laser (Versadisk, ELS) equipped with a frequency doubling unit was used to excite the samples at 515 nm. The set up for detection of the luminescence signal has been reported previously.[17] To calculate the singlet oxygen quantum yield, Φ_Δ, H_2TPP in DMF was used as the reference (Φ_Δ = 0.65[22]).

5^4,10^4,15^4,20^4-Tetra-*tert*-butyl-5^2-cyanomethyl-5^6-methyl-5,10,15,20-tetraphenylporphyrin (4a): Porphyrin system **3a**[9] (209 mg, 0.207 mmol) and powdered KCN (546 mg, 8.93 mmol) were mixed with poly(ethylene glycol) 400 (PEG400) (25 mL). While stirring this mixture at room temperature for 24 h, the pink suspension turned into a deep green-violet solution. Upon addition of water, the product was extracted with CH_2Cl_2 and the combined organic layers were repeatedly washed with water to remove residual cyanide. Then 6 M aqueous HCl was added and the mixture was vigorously shaken for 5 min. After separation of the layers, the organic layer was washed with 2 M HCl, water, a saturated aqueous solution of $NaHCO_3$ and again with water. The solution was dried with $MgSO_4$ and the solvents evaporated to dryness. Flash chromatography (silica, eluent: $CHCl_3$/hexanes = 2:1) gave **4a** as a violet powder. Yield: 176 mg (95% based on **3a**). ^1H NMR (400 MHz): δ = –2.68 (s, 2 H, NH), 1.60 (s, 27 H, *tert*-butyl-H), 1.62 (s, 9 H, *tert*-butyl-H), 1.92 (s, 3 H, CH_3), 3.23 (s, 2 H, CH_2), 7.61 (d, ^4J = 1.5 Hz, 1 H, Ar-H), 7.75 (m, 6 H, Ar-H), 7.80 (d, ^4J = 1.5 Hz, 1 H, Ar-H), 8.14 (m, 6 H, Ar-H), 8.59 (d, ^3J = 4.7 Hz, 2 H, β-pyrr.-H), 8.87 (m, 6 H, β-pyrr.-H) ppm. ^{13}C NMR (100.5 MHz): δ = 21.9, 23.3, 31.6, 31.7, 34.9, 35.0, 114, 118.1, 120.3, 120.9, 122.2, 123.6, 126.3, 131.4, 134.5, 137.9, 138.8, 139.1, 140.0, 150.6, 152.2 ppm. MS: m/z (%) = 893 (100) $[M + H]^+$. IR (ATR): $\tilde{\nu}$ = 3316, 2961, 2903, 2868, 1559, 1505, 1475, 1397, 1363, 1266, 1220, 1189, 1150, 1108, 1023, 965, 849, 803, 737, 714 cm^{-1}. UV/Vis (CH_2Cl_2): λ (ε/M^{-1} cm^{-1}) = 420 (257200), 517 (10360), 552 (4920), 593 (2910), 648 (2160) nm. $C_{63}H_{65}N_5$·0.5$CHCl_3$ (951.92): calcd. C 84.81, H 7.34, N 7.85; found C 79.90, H 7.44, N 6.78.

5^4,10^4,15^4,20^4-Tetra-*tert*-butyl-5^6-methyl-5,10,15,20-tetraphenylporphyrin-5^2-ethanoic Acid (5a): Porphyrin **4a** (176 mg, 197 μmol) was dissolved in glacial acetic acid (15 mL). Then conc. H_2SO_4 (15 mL) and water (5 mL) were added to the green solution and the reaction mixture was stirred at 95 °C for 80 h. Afterwards, the green solution was poured onto crushed ice and left stirring until the crude product precipitated completely. The precipitate was then filtered off, taken up in CH_2Cl_2 and washed with water several times. After drying over $MgSO_4$, the violet solution was concentrated and flash chromatography (silica, eluent: CH_2Cl_2/ethyl acetate = 9:1) fur-

nished **5a** as a violet powder. Yield: 147 mg (82% based on **4a**). ^{1}H NMR (400 MHz): δ = –2.73 (s, 2 H, NH), 1.54 (s, 27 H, *tert*-butyl-H), 1.59 (s, 9 H, *tert*-butyl-H), 1.81 (s, 3 H, Ar-CH_3), 3.24 (s, 2 H, CH_2), 7.49 (s, 2 H, Ar-H), 7.67 (m, 6 H, Ar-H), 8.08 (m, 6 H, Ar-H), 8.59 (d, ^3J = 4.1 Hz, 2 H, β-pyrr.-H), 8.77 (d, ^3J = 4.1 Hz, 2 H, β-pyrr.-H), 8.83 (s, 4 H, β-pyrr.-H) ppm. ^{13}C NMR (100.5 MHz): δ = 23.2, 31.5, 31.6, 34.7, 34.8, 115.1, 116.3, 119.9, 123.5, 123.9, 124.0, 125.2, 134.5, 135.1, 139.0, 139.4, 150.3, 150.5, 151.2, 176.2 ppm. MS: *m*/*z* (%) = 910 (100) $[M]^+$. IR (ATR): $\tilde{\nu}$ 3431, 3107, 2961, 2898, 2866, 1713, 1632, 1557, 1504, 1472, 1396, 1363, 1267, 1184, 1108, 1023, 967, 849, 802, 738 cm^{-1}. UV/Vis (CH_2Cl_2): λ (ε/M^{-1}cm^{-1}) = 420 (313600), 516 (13400), 551 (7300), 592 (4700), 647 (3400) nm. $C_{63}H_{66}N_4O_2{\cdot}H_2O$ (929.24): calcd. C 81.43, H 7.38, N 6.03; found C 81.39, H 7.34, N 5.88.

5^4,10^4,15^4,20^4-Tetra-*tert*-butyl-3,5^2-ethano-5^6-methyl-3^1-oxo-5,10,15,20-tetraphenylporphyrin (2a): Porphyrinacetic acid **5a** (100 mg, 110 μmol) was dissolved in CH_2Cl_2 (30 mL) containing some drops of glacial acetic acid. Then $Cu(OAc)_2$ dihydrate (380 mg, 1.1 mmol) dissolved in MeOH (3 mL) was added and the reaction mixture was stirred for 10 h at room temperature. After evaporation of the solvents the crude mixture was taken up in DMF and poured onto a mixture of crushed ice and acetic acid whereupon the copper(II) complex precipitated. After filtration, washing with water and redissolving in CH_2Cl_2, drying over $MgSO_4$ and evaporation of the solvent furnished the copper complex **6a** as a cherry-red powder. The compound was used as such without further purification and dissolved in CH_2Cl_2 (50 mL). Then oxalyl chloride (2 mL) was added and the reaction mixture was stirred at room temperature for 90 min. Afterwards the resulting acid chloride was dried under high vacuum before it was redissolved in CH_2Cl_2 (30 mL) and $SnCl_4$ (1 mL, 2.23 g, 8.54 mmol) was then added. The brown-red solution thereupon immediately turned dark green. After 10 min the reaction was quenched by careful addition of a saturated aqueous solution of $NaHCO_3$. Extraction with CH_2Cl_2, washing with water, drying over $MgSO_4$ and removal of the solvent yielded the copper(II) complex of **2a** as a mixture with the free base **2a**. Demetallation was obtained by dissolving the obtained mixture in TFA (10 mL) and subsequent addition of concentrated sulfuric acid (2 mL). The now orange-red solution was stirred for 30 min at room temperature before water was added. Extraction with CH_2Cl_2, washing with water, a saturated aqueous solution of $NaHCO_3$ and again with water gave a greenish solution which was dried with $MgSO_4$. A final flash chromatography (silica, eluent: CH_2Cl_2/hexanes = 1:2) gave a dark green powder. Yield: 58 mg (59% based on **5a**). ^{1}H NMR (400 MHz): δ = –1.62 (s, 2 H, NH), 1.17 (s, 3 H, Ar-CH_3), 1.50 (s, 9 H, *tert*-butyl-H), 1.58 (s, 18 H, *tert*-butyl-H), 1.59 (s, 9 H, *tert*-butyl-H), 4.11 (d, ^2J = 11.3 Hz, 2 H, CH_2), 5.49 (d, ^2J = 11.7 Hz, 2 H, CH_2), 7.35 (d, ^4J = 1.7 Hz, 1 H, ArH), 7.68 (d, ^4J = 1.7 Hz, 1 H, ArH), 7.69–8.32 (several m, 12 H, ArH), 8.63 (d, ^3J = 4.9 Hz, 2 H, β-pyrr.-H), 8.67 (d, ^3J = 4.9 Hz, 2 H, β-pyrr.-H), 8.74 (d, ^3J = 4.9 Hz, 2 H, β-pyrr.-H), 8.79 (m, 4 H, β-pyrr.-H), 8.89 (d, ^3J = 4.9 Hz, 2 H, β-pyrr.-H), 8.96 (s, 1 H, β-pyrr.-H) ppm. ^{13}C NMR (100.5 MHz): δ = 22.5, 31.4, 31.6, 34.7, 34.8, 34.9, 53.7, 114.0, 119.0, 122.0, 123.8, 123.9, 124.0, 124.2, 124.6, 125.8, 126.1, 128.3, 134.3, 134.7, 136.1, 137.7, 138.1, 138.5, 138.6, 142.1, 150.8, 150.9, 151.2, 152.3, 192.4 ppm. MS: *m*/*z* (%) = 893 (100) $[M]^+$. IR (ATR): $\tilde{\nu}$ = 3316, 3029, 2957, 2903, 2868, 1683, 1606, 1552, 1498, 1475, 1393, 1363, 1351, 1262, 1239, 1197, 1154, 1108, 1019, 984, 965, 869, 850, 799, 718 cm^{-1}. UV/Vis (CH_2Cl_2): λ (ε/M^{-1}cm^{-1}) = 442 (223000), 543 (11300), 587 (9000), 626 (4100), 689 (9000) nm. $C_{63}H_{64}N_4O{\cdot}H_2O$ (929.24): calcd. C 81.43, H 7.38, N 6.03; found C 81.26, H 7.54, N 5.74.

10^4,15^4,20^4-Tri-*tert*-butyl-5^2-methoxycarbonyl-5,10,15,20-tetraphenylporphyrin (8): Methyl 2-formylbenzoate (**7**)[11] (1.64 g, 10 mmol) was dissolved in $CHCl_3$ (1 L) and 4-*tert*-butylbenzaldehyde (5.0 mL, 30 mmol) as well as pyrrole (2.8 mL, 40 mmol) were added. Upon addition of BF_3–diethyl ether (0.5 mL) the colourless solution slowly turned dark purple. After 75 min, DDQ (4.5 g, 20 mmol)) was added and the reaction mixture was stirred for a further 2 h at room temperature. The crude product was obtained after removal of the solvent and precleaning by filtration through a silica plug using CH_2Cl_2 as eluent. Final purification was achieved by flash chromatography (silica, eluent: hexanes/CH_2Cl_2 = 3:2), furnishing a purple powder. Yield: 1.46 g (17.4% based on **7**). ^{1}H NMR (400 MHz): δ = –2.67 (s, 2 H, NH), 1.61 (s, 18 H, *tert*-butyl-H), 1.62 (s, 9 H, *tert*-butyl-H), 2.72 (s, 3 H, OCH_3), 7.76 (m, 7 H, Ar-H), 7.82 (dd, ^3J = 7.3 Hz, ^4J = 1.7 Hz, 1 H, Ar-H), 7.86 (dt, ^3J = 7.8 Hz, ^4J = 1.5 Hz, 1 H, Ar-H), 8.15 (m, 6 H, Ar-H), 8.40 (dd, ^3J = 7.7 Hz, ^4J = 1.6 Hz, Ar-H), 8.66 (d, ^3J = 4.8 Hz, 2 H, β-pyrr.-H) 8.87 (d, ^3J = 4.8 Hz, 2 H, β-pyrr.-H), 8.89 (s, 4 H, β-pyrr.-H) ppm. ^{13}C NMR (100.5 MHz): δ = 31.6, 34.8, 51.5, 118.7, 120.2, 120.3, 123.6, 128.3, 129.6, 129.7, 134.2, 134.5, 136.1, 139.2, 139.2, 142.7, 150.5, 168.2 ppm. MS: *m*/*z* (%) = 841 (100) $[M]^+$. IR: $\tilde{\nu}$ = 3319, 3028, 2961, 2902, 2867, 1735, 1720, 1473, 1398, 1362, 1349, 1291, 1257, 1108, 1084, 968, 801, 734 cm^{-1}. UV/Vis: λ (ε/M^{-1}cm^{-1}) = 419 (267400), 516 (9900), 552 (5600), 592 (3200), 649 (2400) nm. $C_{58}H_{56}N_4O_2{\cdot}0.5H_2O$ (850.10): calcd. C 81.95, H 6.76, N 6.59; found C 81.81, H 6.86, N 6.43.

10^4,15^4,20^4-Tri-*tert*-butyl-5^2-hydroxymethyl-5,10,15,20-tetraphenylporphyrin (9): Porphyrin ester **8** (300 mg) was dissolved in CH_2Cl_2 (50 mL) and a saturated solution of $Zn(OAc)_2$ dihydrate in methanol (5 mL) was added. The reaction mixture was then stirred at room temperature until TLC control showed completion. Addition of water, extraction with CH_2Cl_2, repeated washing with water, drying over $MgSO_4$ and evaporation of the solvent yielded the purple zinc(II) complex of **8** almost quantitatively. This sample was taken up in THF (50 mL) and an excess of $LiAlH_4$ was added. After 30 min of stirring at room temperature, methanol was carefully added to destroy residual $LiAlH_4$. Upon addition of 6 M HCl, extraction with CH_2Cl_2, repeated washing with water, a saturated aqueous solution of $NaHCO_3$ and again with water, a dark purple solution was obtained which was dried with $MgSO_4$. Evaporation of the solvent furnished the crude desired benzylic alcohol **9**. Flash chromatography (silica, eluent: hexanes/CH_2Cl_2 = 3:5) yielded pure **9** in 87% yield based on **8**. ^{1}H NMR (400 MHz): δ = –2.71 (s, 2 H, NH), 1.21 (t, ^3J = 5.6 Hz, 1 H, OH), 1.60 (s, 18 H, *tert*-butyl-H), 1.61 (s, 9 H, *tert*-butyl-H), 4.31 (d, ^3J = 5.2 Hz, 2 H, CH_2), 7.64 (dt, ^3J = 7.6 Hz, ^4J = 0.9 Hz, 1 H, Ar-H), 7.75 (m, 6 H, Ar-H), 7.81 (t, ^3J = 7.6 Hz, 1 H, Ar-H), 7.89 (d, ^3J = 7.7 Hz, 1 H, Ar-H), 8.13 (br. m, 7 H, Ar-H), 8.66 (d, ^3J = 4.7 Hz, 2 H, β-pyrr.-H), 8.88 (m, 6 H, β-pyrr.-H) ppm. ^{13}C NMR (100.5 MHz): δ = 31.7, 34.9, 63.8, 116.5, 120.4, 120.7, 123.6, 125.7, 126.9, 128.8, 131.2, 131.5, 134.1, 134.4, 138.9, 139.2, 140.3, 142.3, 150.5 ppm. MS: *m*/*z* (%) = 813 (100) $[M]^+$. IR: $\tilde{\nu}$ = 3410, 3028, 2960, 2903, 2866, 1809, 1606, 1559, 1505, 1473, 1396, 1362, 1348, 1266, 1193, 1153, 1108, 1023, 993, 981, 967, 881, 849, 801 cm^{-1}. UV/Vis: λ (ε/M^{-1}cm^{-1}) = 420 (285200), 517 (10400), 552 (5200), 591 (3100), 646 (2000) nm. $C_{57}H_{56}N_4O{\cdot}0.5H_2O$ (822.09): calcd. C 83.28, H 6.99, N 6.81; found C 83.43, H 6.99, N 6.82.

5^2-Bromomethyl-10^4,15^4,20^4-tri-*tert*-butyl-5,10,15,20-tetraphenylporphyrin (3b): Porphyrin **9** (252 mg) was dissolved in CH_2Cl_2 (50 mL) and an excess of HBr (5.4 M in glacial acetic acid, 10 mL) was added whereupon the purple solution turned dark green immediately. After 3 h water was added and the phases were separated. Repeated washing with water, neutralization with a saturated aque-

ous solution of $NaHCO_3$, washing with water, drying over $MgSO_4$ and evaporation of the solvent yielded a mixture of the desired product and an acetoxymethylporphyrin. Separation was achieved by flash chromatography (silica, eluent: hexanes/CH_2Cl_2 = 1:2), yielding 101 mg of a violet powder (37% yield based on **9**). ^1H NMR (400 MHz): δ = –2.59 (s, 2 H, NH), 1.65 (s, 27 H, *tert*-butyl-H), 4.31 (s, 2 H, CH_2), 7.64 (dt, ^3J = 7.6 Hz, ^4J = 1.4 Hz, 1 H, Ar-H), 7.80 (br. m, 7 H, Ar-H), 7.92 (dd, ^3J = 8.1 Hz, ^4J = 1.0 Hz, 1 H, Ar-H), 8.13 (dd, ^3J = 7.6 Hz, ^4J = 1.0 Hz, 1 H, Ar-H), 8.21 (m, 6 H, Ar-H), 8.73 (d, ^3J = 4.7 Hz, 2 H, β-pyrr.-H), 8.97 (m, 6 H, β-pyrr.-H) ppm. ^{13}C NMR (100.5 MHz): δ = 31.6, 31.8, 34.9, 115.7, 120.4, 120.8, 123.6, 126.5, 129.1, 129.7, 131.4, 134.5, 139.0, 139.2, 139.3, 141.6, 150.5 ppm. MS: *m*/*z* (%) = 876 (100) $[M]^+$, 795 (40) $[M – Br]^+$. IR: $\tilde{\nu}$ = 3318, 3028, 2962, 2867, 2360, 1474, 1396, 1363, 1349, 1267, 1220, 1108, 1023, 967, 801, 736 cm^{-1}. UV/Vis: λ (ε/$M^{-1}cm^{-1}$) = 420 (303800), 515 (12100), 551 (6000), 590 (3800), 646 (3200) nm. $C_{57}H_{55}N_4Br{\cdot}CH_2Cl_2$ (960.91): C 75.19, H 6.15, N 6.10; found C 75.01, H 6.11, N 5.99.

10^4,15^4,20^4-Tri-*tert*-butyl-5^2-cyanomethyl-5,10,15,20-tetraphenylporphyrin (4b): Bromomethylporphyrin **3b** (101 mg) was dissolved in CH_2Cl_2 (25 mL) and a saturated solution of $Zn(OAc)_2$ dihydrate in methanol (3 mL) was added. The reaction mixture was then stirred at room temperature until TLC control showed completion. Addition of water, extraction with CH_2Cl_2, repeated washing with water, drying over $MgSO_4$ and evaporation of the solvent yielded the purple zinc(II) complex of **3b** quantitatively. The zinc(II) complex thus obtained (108 mg, 115 μmol) and powdered KCN (375 mg, 5.75 mmol) were mixed with poly(ethylene glycol) 400 (PEG400) (25 mL). While stirring this mixture at room temperature for 24 h, the pink suspension turned into a deep green-violet solution. Upon addition of water, the product was extracted with CH_2Cl_2 and the combined organic layers were repeatedly washed with water to remove residual cyanide. Then 6 M aqueous HCl was added and the mixture was vigorously shaken for 5 min. After separation of the layers, the organic layer was washed with 2 M HCl, water, a saturated aqueous solution of $NaHCO_3$ and again water. The solution was dried with $MgSO_4$ and the solvents evaporated to dryness. FC (silica, eluent: CH_2Cl_2/hexanes = 2:1) gave **4b** as a violet powder. Yield: 90 mg (110 μmol, 95% based on **3a**). ^1H NMR (400 MHz): δ = –2.63 (s, 2 H, NH), 1.64 (s, 27 H, *tert*-butyl-H), 3.42 (s, 2 H, CH_2), 7.73 (dt, ^3J = 7.6 Hz, ^4J = 1.2 Hz, 1 H, Ar-H), 7.78 (br. m, 7 H, Ar-H), 7.87 (dt, ^3J = 7.6 Hz, ^4J = 1.4 Hz, 1 H, Ar-H), 7.98 (d, ^3J = 7.8 Hz, 1 H, Ar-H), 8.18 (br. m, 6 H, Ar-H), 8.66 (d, ^3J = 4.8 Hz, 2 H, β-pyrr.-H), 8.95 (s, 4 H, β-pyrr.-H), 8.96 (d, ^3J = 4.8 Hz, 2 H, β-pyrr.-H) ppm. ^{13}C NMR (100.5 MHz): δ = 22.8, 31.6, 34.9, 114.9, 117.8, 120.6, 121.1, 123.6, 126.6, 127.5, 129.3, 132.0, 134.3, 134.4, 138.8, 139.0, 141.3, 150.6 ppm. MS: *m*/*z* (%) = 823 (100) $[M + H]^+$. IR: $\tilde{\nu}$ = 3315, 2962, 2903, 2866, 1558, 1510, 1476, 1397, 1363, 1268, 1220, 1187, 1150, 1109, 1025, 965, 849, 803, 738, 715 cm^{-1}. UV/Vis: λ (ε/$M^{-1}cm^{-1}$) = 420 (256300), 516 (9530), 552 (4930), 591 (2850), 647 (2100) nm. $C_{58}H_{55}N_5{\cdot}H_2O$ (840.11): calcd. C 82.92, H 6.84, N 8.34; found C 82.67, H 6.79, N 8.19.

10^4,15^4,20^4-Tri-*tert*-butyl-5,10,15,20-tetraphenylporphyrin-5^2-ethanoic Acid (5b): Porphyrin **4b** (90 mg, 110 μmol) was dissolved in glacial acetic acid (10 mL). Then concentrated H_2SO_4 (10 mL) and water (3 mL) were added and the reaction mixture was stirred at 95 °C for 80 h. Afterwards, the green solution was poured onto crushed ice and stirred until the crude product had completely precipitated. The precipitate was then filtered off, taken up in CH_2Cl_2 and washed with water several times. After drying over $MgSO_4$, the violet solution was concentrated and flash chromatography (silica, eluent: CH_2Cl_2/ethyl acetate = 9:1) furnished **5b** as a violet powder. Yield: 79 mg (85% based on **4b**). ^1H NMR (400 MHz): δ = –2.74 (s, 2 H, NH), 1.54 (s, 18 H, *tert*-butyl-H), 1.61 (s, 9 H, *tert*-butyl-H), 3.35 (s, 2 H, CH_2), 7.54–7.71 (m′s, 7 H, Ar-H), 7.75 (d, ^3J = 8.6 Hz, 2 H, Ar-H), 8.03 (m, 1 H, Ar-H), 8.06 (d, ^3J = 8.6 Hz, 4 H, Ar-H), 8.11 (d, ^3J = 7.0 Hz, 1 H, Ar-H), 8.15 (d, ^3J = 8.1 Hz, 1 H, Ar-H), 8.60 (d, ^3J = 4.8 Hz, 2 H, β-pyrr.-H), 8.79 (d, ^3J = 4.8 Hz, 2 H, β-pyrr.-H), 8.83 (d, ^3J = 4.7 Hz, 2 H, β-pyrr.-H), 8.86 (d, ^3J = 4.7 Hz, 2 H, β-pyrr.-H) ppm. ^{13}C NMR (100.5 MHz): δ = 25.6, 31.6, 31.7, 34.7, 39.0, 116.7, 120.3, 120.6, 123.6, 125.5, 128.6, 129.3, 131.3, 134.4, 135.4, 139.0, 139.2, 141.9, 150.4, 150.5, 175.3 ppm. MS: *m*/*z* (%) = 841 (100) $[M]^+$. IR: $\tilde{\nu}$ = 3320, 3028, 2962, 2867, 1691, 1598, 1475, 1398, 1350, 1297, 985, 802, 721 cm^{-1}. UV/Vis: λ (ε/$M^{-1}cm^{-1}$) = 420 (257400), 517 (9200), 552 (4900), 592 (3000), 648 (2200) nm. $C_{58}H_{56}N_4O_2{\cdot}H_2O$ (870.12): calcd. C 79.42, H 6.89, N 6.39; found C 79.20, H 6.75, N 6.14.

10^4,15^4,20^4-Tri-*tert*-butyl-3,5^2-ethano-3^1-oxo-5,10,15,20-tetraphenylporphyrin (2b): Porphyrin **2b** was prepared following the procedure described above for the synthesis of **2a**. Starting materials: **5b** (79 mg, 94 μmol) and $Cu(OAc)_2$ dihydrate (325 mg, 0.94 mmol). Amounts of solvents, other reagents and catalysts as well as the purification protocol were exactly the same. Yield: 50 mg as a dark green powder (61 μmol, 65% based on **5b**). ^1H NMR (400 MHz): δ = –1.70 (s, 2 H, NH), 1.59 (s, 9 H, *tert*-butyl-H), 1.60 (s, 9 H, *tert*-butyl-H), 1.61 (s, 9 H, *tert*-butyl-H), 4.20 (d, ^2J = 11.8 Hz, 1 H, CH_2), 5.59 (d, ^2J = 11.8 Hz, 1 H, CH_2), 7.19 (dd, ^3J = 7.5 Hz, ^4J = 1.1 Hz, 1 H, Ar-H), 7.54 (m, 2 H, Ar-H), 7.81 (br. m, 7 H, Ar-H), 8.00 (d, ^3J = 7.0 Hz, 1 H, Ar-H), 8.19 (d, ^3J = 7.3 Hz, 1 H, Ar-H), 8.31 (br. s, 2 H, Ar-H), 8.71 (d, ^3J = 4.7 Hz, 1 H, β-pyrr.-H), 8.76 (d, ^3J = 4.7 Hz, 1 H, β-pyrr.-H), 8.82 (d, ^3J = 4.8 Hz, 1 H, β-pyrr.-H), 8.84 (d, ^3J = 4.8 Hz, 1 H, β-pyrr.-H), 8.90 (d, ^3J = 4.9 Hz, 1 H, β-pyrr.-H), 9.09 (d, ^3J = 4.9 Hz, 1 H, β-pyrr.-H), 9.16 (s, 1 H, β-pyrr.-H) ppm. ^{13}C NMR (100.5 MHz): 31.6, 34.9, 52.6, 115.8, 119.5, 121.9, 123.8, 125.3, 126.9, 127.2, 127.9, 129.9, 134.2, 138.1, 138.3, 138.5, 141.0, 141.3, 150.7, 150.8, 151.0, 191.5 ppm. MS: *m*/*z* (%) = 823 (100) $[M]^+$. IR (ATR): $\tilde{\nu}$ = 3320, 3030, 2961, 2903, 2868, 1725, 1679, 1552, 1502, 1471, 1397, 1363, 1266, 1197, 1158, 1108, 1073, 1023, 984, 965, 911, 849, 802, 729 cm^{-1}. UV/Vis: λ (ε/$M^{-1}cm^{-1}$) = 438 (182000), 540 (8200), 584 (7100), 686 (5000) nm. $C_{58}H_{54}N_4O{\cdot}H_2O$ (841.09): calcd. C 82.82, H 6.71, N 6.66; found C 82.53, H 6.68, N 6.42.

10^4,15^4,20^4-Tri-*tert*-butyl-5,10,15,20-tetraphenylporphyrin-5^2-methanoic Acid (5c): Porphyrin **8** (300 mg, 357 μmol) was dissolved in a mixture of THF (10 mL), water (10 mL) and ethanol (100 mL) containing 5 wt.-% of powdered KOH. The mixture was then stirred under reflux for 12 h. After addition of water the precipitated porphyrinmethanoic acid derivative was collected by filtration, washed with water and taken up in CH_2Cl_2. Neutralization with 2 M HCl, washing with water and drying with $MgSO_4$ gave the crude product which was purified by FC (silica, first elution: CH_2Cl_2, second elution: EtOAc). Yield: 277 mg (335 μmol, 94% based on **8**). ^1H NMR (300 MHz, $CDCl_3$/[D_8]THF): δ = –2.72 (s, 2 H, NH), 1.56 (s, 27 H, *tert*-butyl-H), 7.68–7.76 (m, 8 H, Ar-H), 8.08–8.11 (m, 7 H, Ar-H), 8.31 (m, 1 H, Ar-H), 8.61 (d, ^3J = 4.7 Hz, 2 H, β-pyrr.-H), 8.77–8.81 (m, 6 H, β-pyrr.-H) ppm. ^{13}C NMR (100.5 MHz): δ = 31.6, 34.8, 119.1, 119.9, 120.0, 123.5, 128.1, 129.3, 129.8, 130.8, 134.4, 134.6, 135.9, 139.1, 139.3, 142.6, 150.3, 168.7 ppm. MS: *m*/*z* (%) = 827 (100) $[M]^+$. IR: $\tilde{\nu}$ = 3316, 3030, 2961, 2868, 1691, 1598, 1471, 1397, 1351, 1297, 984, 799, 721 cm^{-1}. UV/Vis: λ (ε/$M^{-1}cm^{-1}$) = 420 (265300), 517 (10000), 552 (5100), 592 (3100), 648 (2500) nm. $C_{57}H_{54}N_4O_2{\cdot}1.5H_2O$ (854.09): calcd. C 80.16, H 6.73, N 6.56; found C 80.41, H 6.62, N 6.37.

10^4,15^4,20^4-Tri-*tert*-butyl-3,5^2-methano-3^1-oxo-5,10,15,20-tetraphenylporphyrin (2c): Porphyrin 2c was prepared following de-

scribed above for the synthesis of **2a**. Starting materials: **5c** (100 mg, 121 μmol) and $Cu(OAc)_2$ dihydrate (418 mg, 1.21 mmol). Amounts of solvents, other reagents and catalysts as well as the purification protocol were exactly the same. Yield: 60 mg as a dark green powder (74 μmol, 61% based on **5c**). ^{1}H NMR (400 MHz): δ = –0.55 (s, 2 H, NH), 1.56 (s, 9 H, *tert*-butyl-H), 1.58 (s, 18 H, *tert*-butyl-H), 7.44 (t, ^3J = 7.3 Hz, 1 H, Ar-H), 7.72 (m, 7 H, Ar-H), 8.00 (m, 6 H, Ar-H), 8.29 (d, ^3J = 7.9 Hz, 1 H, Ar-H), 8.47 (dd, ^3J = 7.7 Hz, ^4J = 1.1 Hz, 1 H, Ar-H), 8.50 (d, ^3J = 4.8 Hz, 1 H, β-pyrr.-H), 8.56 (m, 2 H, β-pyrr.-H), 8.62 (m, 2 H, β-pyrr.-H), 9.24 (m, 2 H, β-pyrr.-H) ppm. ^{13}C NMR (100.5 MHz): δ = 31.7, 34.9, 110.5, 118.2, 121.0, 123.2, 123.9, 126.3, 127.4, 129.3, 133.2, 134.1, 134.4, 134.5, 136.5, 137.5, 138.0, 138.3, 151.0, 151.1, 192.0 ppm. MS: *m*/*z* (%) = 809 (100) $[M]^+$. IR: $\tilde{\nu}$ = 3300, 3065, 3030, 2961, 2903, 2868, 2247, 1725, 1648, 1590, 1556, 1525, 1505, 1463, 1397, 1363, 1293, 1279, 1216, 1197, 1162, 1108, 1023, 984, 965, 911, 849, 802, 730 cm^{-1}. UV/Vis: λ (ε/M^{-1} cm^{-1}) = 332 (24900), 395 (35500), 465 (99500), 533 (3000), 579 (5000), 644 (7700), 745 (9300) nm. $C_{57}H_{52}N_4O{\cdot}H_2O$ (845.08): calcd. C 81.01, H 6.68, N 6.63; found C 80.85, H 6.61, N 6.40.

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[1] K. M. Kadish, K. M. Smith, R. Guilard (Eds.), *The Porphyrin Handbook*, Academic Press, San Diego, **2000**.
[2] a) E. S. Nyman, P. H. Hynninen, *J. Photochem. Photobiol. B* **2004**, *73*, 1–28; b) A. P. Castano, T. N. Demidova, M. R. Hamblin, *Photodiag. Photodyn. Therapy* **2004**, *1*, 279–293; c) A. P. Castano, T. N. Demidova, M. R. Hamblin, *Photodiag. Photodyn. Therapy* **2005**, *2*, 1–23; d) A. P. Castano, T. N. Demidova, M. R. Hamblin, *Photodiag. Photodyn. Therapy* **2005**, *2*, 91–106.
[3] H. V. Tappeiner, A. Jesionek, *Muench. Med. Wochenschr.* **1903**, *50*, 2042–2044.
[4] a) T. J. Dougherty, G. B. Grindey, R. Fiel, K. R. Weishaupt, D. G. Boyle, *J. Natl. Cancer Inst.* **1975**, *55*, 150; b) T. J. Dougherty, J. H. Kaufman, A. Goldfarb, K. R. Weishaupt, D. Boyle, A. Mittleman, *Cancer Res.* **1978**, *38*, 2628.
[5] K. Berg, P. K. Selbo, A. Weyergang, A. Dietze, L. Prasmickaite, A. Bonsted, B. Ø. Engesaeter, E. Angell-Petersen, T. Warloe, N. Frandsen, A. Høgset, *J. Microscopy* **2005**, *218*, 133–147.
[6] E. D. Sternberg, D. Dolphin, C. Brückner, *Tetrahedron* **1998**, *54*, 4151–4202.
[7] a) S.-I. Moriwaki, J. Misawa, Y. Yoshinari, I. Yamada, M. Takigawa, Y. Tokura, *Photodermatol. Photoimmunol. Photomed.* **2001**, *17*, 241–243; b) T. J. Dougherty, M. T. Cooper, T. S. Mang, *Lasers Surg Med* **1990**, *10*, 485–488; c) M. Ochsner, *J. Photochem. Photobiol. B* **1997**, *39*, 1–18.
[8] For example, see: a) A. Osuka, Y. Wada, S. Shinoda, *Tetrahedron* **1996**, *52*, 4311–4326; b) P. H. Hynninen, *Z. Naturforsch., Teil B* **1981**, *36*, 1000–1009; c) K. M. Smith, D. A. Goff, R. J. Abraham, *J. Org. Chem.* **1987**, *52*, 176–180.
[9] N. H. Huyen, U. Jannsen, H. Mansour, N. Jux, *J. Porphyrins Phthalocyanines* **2004**, *8*, 1356–1365.
[10] a) S. Richeter, C. Jeandon, N. Kyritsakas, R. Ruppert, H. J. Callot, *J. Org. Chem.* **2003**, *68*, 9200–9208; b) S. Richeter, C. Jeandon, R. Ruppert, H. J. Callot, *Tetrahedron Lett.* **2001**, *42*, 2103–2106.
[11] B.-H. Ye, Y. Naruta, *Tetrahedron* **2003**, *59*, 3593–3601.
[12] C. J. Medforth in *The Porphyrin Handbook* (Eds.: K. M. Kadish, K. M. Smith, R. Guilard), Academic Press, San Diego, **2000**, pp. 1–80.
[13] Materials Studio®, Version 2.2.1, © **2002**, Accelrys Inc., www.materials-studio.com.
[14] a) K. Ishii, N. Kobayashi in *The Porphyrin Handbook*, vol. 16 (Eds.: K. M. Kadish, K. M. Smith, R. Guilard), Academic Press, San Diego, California, **2003**, pp. 1–42; b) N. Kobayashi, Y. Higashi, T. Osa, *Chem. Lett.* **1994**, 1813–1817.
[15] E. A. Lissi, M. V. Encinas, E. Lemp, M. A. Rubio, *Chem. Rev.* **1993**, *93*, 699–723.
[16] J. R. Darwent, P. Douglas, A. Harriman, G. Porter, M.-C. Richoux, *Coord. Chem. Rev.* **1982**, *44*, 83–126.
[17] W. Spiller, H. Kliesch, D. Wöhrle, S. Hackbarth, B. Röder, G. Schnurpfeil, *J. Porphyrins Phthalocyanines* **1998**, *2*, 145–158.
[18] E. Zenkevich, E. Sagun, V. Knyukshto, A. Shulga, A. Mironow, O. Efremova, R. Bonnett, S. P. Songea, M. Kassem, *Photochem. Photobiol. B: Biol.* **1997**, *33*, 171–180.
[19] O. Korth, Th. Hanke, I. Rückmann, B. Röder, *Exp. Technol. Phys.* **1995**, *41*, 25–36.
[20] P. G. Seybold, M. P. Gouterman, *J. Mol. Spectrosc.* **1969**, *31*, 1–13.
[21] I. Rückmann, A. Zeug, R. Herter, B. Röder, *Photochem. Photobiol.* **1997**, *66*, 576–584.
[22] B. M. Dzhagarov, K. I. Salokhiddinov, G. D. Egorova, G. P. Gurinovich, *Russ. J. Phys. Chem.* **1987**, *61*, 1281–1283.

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