LETTER

NJC
www.rsc.org/njc

A photoactive nona-porphyrin with nucleosidic linkers

Nathalie Solladié,*[a] Chloé Sooambar,[a] Haiko Herschbach,[b] Jean-Marc Strub,[b] Emmanuelle Leize,[b] Alain Van Dorsselaer,*[b] Anna Maria Talarico,[c] Barbara Ventura[c] and Lucia Flamigni*[c]

[a] *Groupe de Synthèse de Systèmes Porphyriniques, Laboratoire de Chimie de Coordination du CNRS (UPR 8241), 205 route de Narbonne, 31077 Toulouse Cedex 4, France. E-mail: solladie@lcc-toulouse.fr; Fax: +33 5 61 55 30 03*

[b] *Laboratoire de Spectrométrie de Masse Bio-organique, Université Louis Pasteur and CNRS, Ecole de Chimie, Polymères et Matériaux (ECPM), 25 rue Becquerel, 67200 Strasbourg, FranceE-mail: vandors@chimie.u-strasbg.fr*

[c] *Istituto per la Sintesi Organica e Fotoreattivita' (ISOF), CNR, Via P. Gobetti 101, 40129 Bologna, ItalyE-mail: flamigni@isof.cnr.it*

Received (in Montpellier, France) 12th July 2005, Accepted 26th September 2005
First published as an Advance Article on the web 10th October 2005

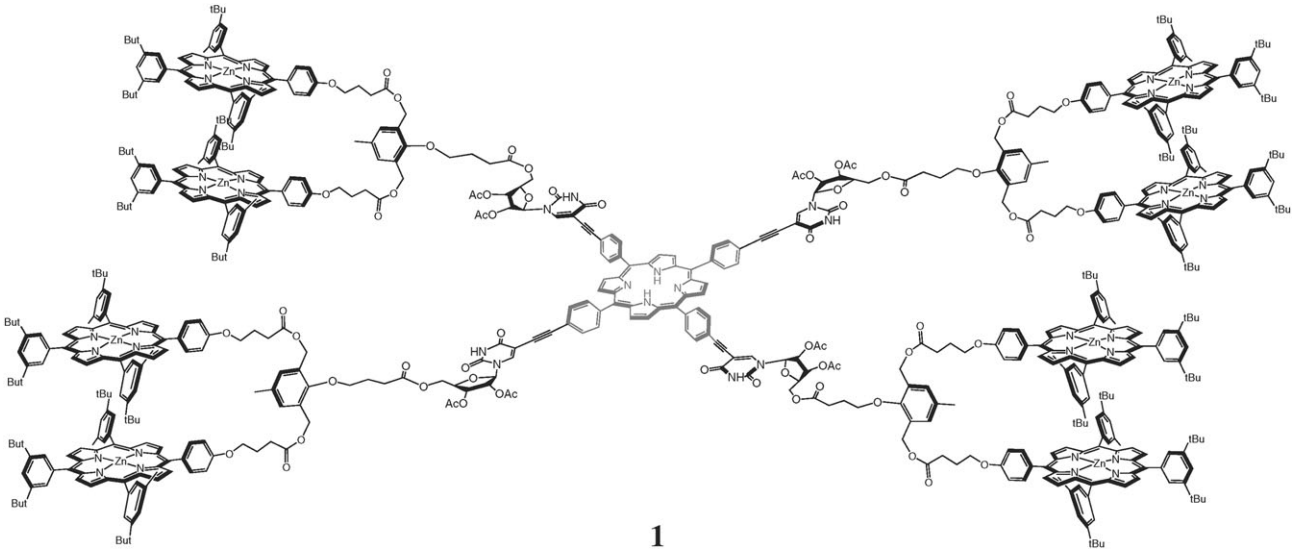
A nona-porphyrin constituted of eight Zn(II) porphyrins anchored to a tetra-nucleosidic free-base porphyrin has been synthesized for its light absorbance capability and its ability to deliver this energy to the central chromophore.

In the light harvesting part of the photosynthetic system, solar energy is collected by chlorophylls. The absorption of a photon by a pigment in these antennae is followed by the extremely fast migration of the excited state among the pool of chlorophylls with minimal energy loss until the reaction center is reached. Located within the cell membrane, this center shelters the conversion of solar energy into chemical energy, which in turn is used by the cells to propel protons across the membrane.[1] With the aim of mimicking these antenna complexes, multi-porphyrinic dendrimers have attracted growing interest.[2] Increasing the number of chromophores around one single energy acceptor enhances the probability of capturing a photon and thus transferring energy towards the central chromophore. We report herein the synthesis of nona-porphyrin **1**, constituted of eight Zn(II) porphyrins anchored to a central tetra-nucleosidic free-base porphyrin and dedicated to both collection of photons and delivery of their energy to the central free-base porphyrin (Fig. 1). This multi-chromophore photoactive device was designed as a higher oligomer of the penta-porphyrin we reported a few years ago[3] in which only four Zn(II) porphyrins are attached to the tetra-nucleosidic core chromophore. As such, nona-porphyrin **1** may be considered as part of the second generation of a new class of arborescent molecules, for which the number of peripheral chromophores is increased without addition of any intermediate susceptible of reducing the efficiency of energy transfer toward the center of the molecular device.

The synthesis of the high molecular weight multi-porphyrinic array **1** is based on the stepwise functionalization of uridine at both C-5′ position of the ribose and C-5 position of the uracil nucleic base (**5** on Scheme 1). The synthesis of the uridine derivative **4** was previously reported.[3] Iodination at C-5 allows coupling of *p*-(ethynyl)-benzaldehyde while protection of both O-2′ and O-3′ alcohols is necessary to selectively direct an esterification reaction to take place at O-5′. Although only one Zn(II) porphyrin is anchored on the ribose for the synthesis of our previously described penta-porphyrin,[3] a synthon containing two Zn(II) porphyrins (**3**) is here linked at the O-5′ position of the sugar. Compound **3** was synthesized in four steps from 4-bromobutyric acid, 2,6-bis(hydroxymethyl)-*p*-cresol and 4-{4-[10,15,20-tris-(3,5-di-*tert*-butyl-phenyl)-porphyrin-5-yl]-phenoxy}-butyric acid.[3] A silyl protective group has been chosen for the mild conditions required for the deprotection of the carboxylic acid function, compatible with the presence of labile cations inside the porphyrinic rings. After esterification of alcohol **4** by the bis-porphyrin **3**, the nucleoside–porphyrin conjugate **5**,[3,4] as the key intermediate, bears two Zn(II) porphyrins at C-5′ position of the ribose and one aldehydic function at the C-5 position of the uracil nucleic base. The construction of nona-porphyrin **1** in one step from precursor **5** is based on the latter aldehyde. **1** was obtained by construction of the central porphyrin under the conditions developed by Lindsey for the synthesis of sterically hindered porphyrins (Scheme 1).[5] Compound **1** was isolated with 35% yield after tedious purification by successive column chromatography on silica gel, followed by gel permeation chromatography (GPC) to remove some low molecular weight impurities which could not be removed by classical chromatography.

The identification of nona-porphyrin **1** by MALDI-TOF mass spectrometry could only be obtained upon addition of TFA to the sample. Such an acidification of the medium resulted in full demetallation of the nona-porphyrin to its free-base analog, which could be identified as its mono-protonated derivative (11251.1, $[M - 8Zn^{2+} + 16H^+ + H^+]^+$, calcd: 11251.8). The purity of nona-porphyrin **1** was then confirmed by elemental analysis ($C_{732}H_{796}N_{44}O_{64}Zn_8 \cdot CH_2Cl_2$, calcd. C, 73.1; H, 6.7; N, 5.1; found. C, 72.9; H, 6.9; N, 5.2%). ^{1}H-NMR spectroscopy experiments were carried out at room temperature and under heating, but only ill resolved spectra were obtained. A fine structure emerged in the ^{1}H-NMR spectrum recorded at 400 K, but it was not resolved enough to allow clear interpretation of the spectrum. However, the signal at ~9 ppm corresponding to the β-pyrrolic protons which barely appears as a doublet at 300 K spreads into one singlet and one AB system at 400 K, thus showing the expected ^{1}H-NMR signature of the peripheral A_3B porphyrins. Even though no fine structure could be obtained upon heating, prohibiting the clear interpretation of the ^{1}H-NMR spectrum, these studies clearly demonstrate that rather slow conformational motions (on the NMR time-scale) exist for this nona-porphyrin. The CD spectrum represented on Fig. 2 highlights unexpected

DOI: 10.1039/b509913g

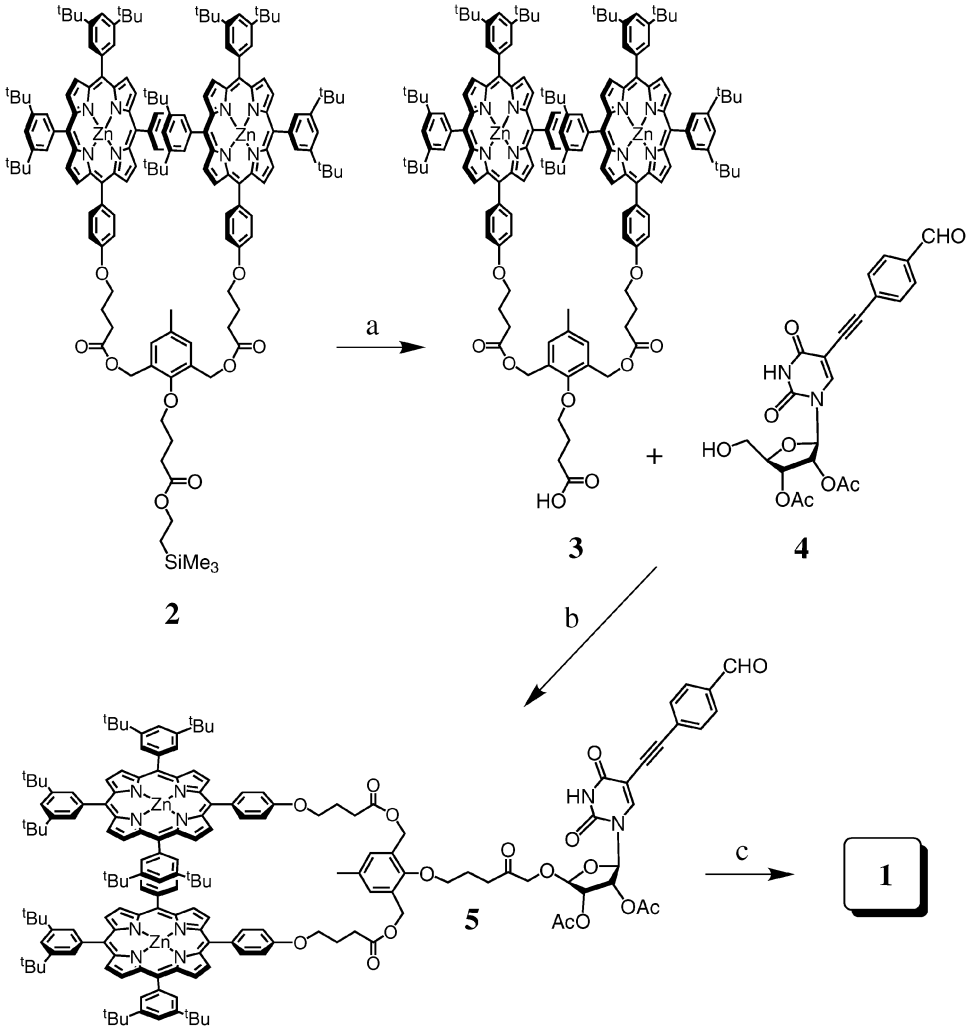


1

Fig. 1 Tetra-nucleosidic nona-porphyrin **1**.

features concerning the conformations adopted by nona-porphyrin **1**. Optical activity is displayed by compound **1**, which can be assigned to exciton interactions between the porphyrins.[3–7] Since only the uridine spacer is chiral, the optical activity of **1** can be attributed to a porphyrin helicity induced by the enantio-purity of the nucleosidic linkers. Indeed, the intrinsic optical activity of the nucleosidic fragment can be detected on the bands of this unit appearing further in the UV spectral region. Further investigations concerning the type of helicity adopted by the porphyrins in nona-porphyrin **1** are currently under way.

The absorption spectrum of **1** in toluene matches quite well a superposition of the nine porphyrin constituent units, indicating a modest electronic coupling between components. The



Scheme 1 *Reagents and conditions:* (a) TBAF, DMF, rt, 7 h, 94%. (b) DCC–DMAP, CH_2Cl_2, rt, 7 h, 50%. (c) pyrrole, $CHCl_3$, $BF_3 \cdot OEt_2$ cat., rt, 48 h then *p*-chloranil, reflux, 3 h, 35%.

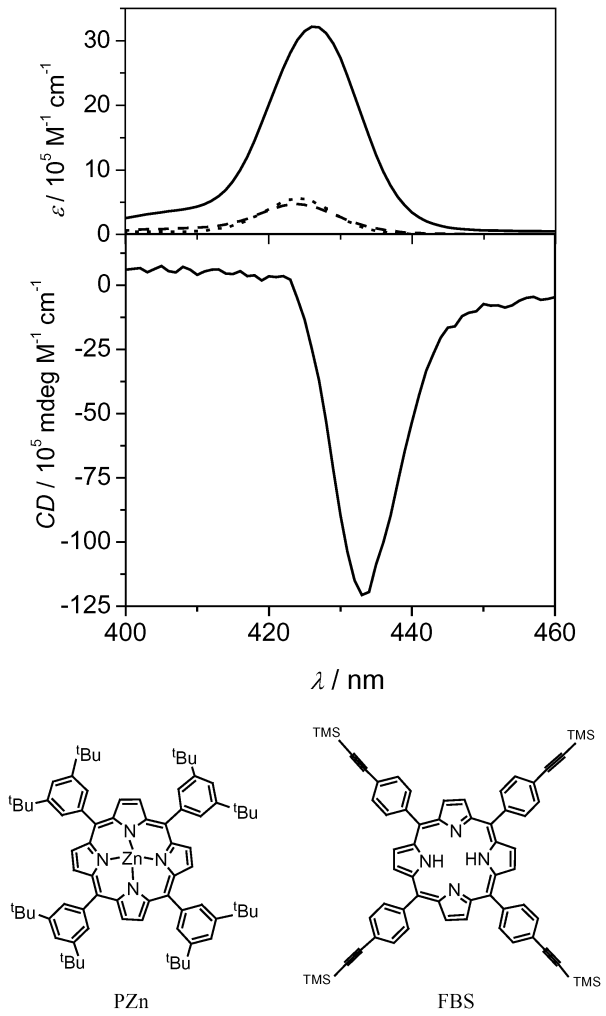


Fig. 2 UV (upper panel) and CD (lower panel) spectra of nona-porphyrin **1** (solid line) in toluene solutions. In the upper panel, the absorption spectra of components, the Zn(II) porphyrin PZn (dotted line) and the free-base porphyrin FBS (dashed line).

luminescence spectrum of **1** (Fig. 3) displays bands at 600, 651 and 719 nm, which can be respectively assigned to the Zn(II) porphyrin (595 and 645 nm) and to the free-base porphyrin constituent (653 nm and 719 nm). The excitation spectrum of the emission registered at 720 nm, where only the central free-base unit emits, displays an important contribution at 552 nm (Fig. 3, inset A) where Zn(II) porphyrin has a strong absorption band. This indicates an efficient energy transfer from the Zn porphyrin periphery to the free-base core.

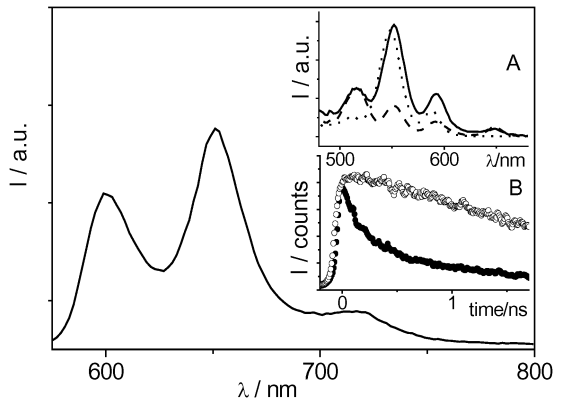


Fig. 3 Luminescence spectrum of **1** (λ_{exc} = 550 nm). The excitation spectrum of **1** (solid line), of the model Zn(II) porphyrin PZn (dotted line) and free-base porphyrin FBS (dashed line) are reported in inset A. In inset B the luminescence decay of **1** (filled circles) is shown with the decay of the model Zn(II) porphyrin PZn (empty circles), excitation at 532 nm.

Time resolved luminescence experiments with picosecond resolution of **1** in toluene confirm the existence of fast quenching processes at 600 nm for the Zn(II) porphyrin unit in **1** when compared with the reference model PZn (Fig. 3, inset B). The luminescence decay at 600 nm of **1** can be fitted by a tri-exponential law, with lifetimes of 0.175, 0.990 and 2.2 ns with relative weight of 50%, 30% and 20%, respectively. A multi-exponential behavior is typical of the Zn(II) porphyrin donor luminescence decay in either flexible or rigid dendritic multi-porphyrin arrays for light harvesting and is due to the existence of several donor–acceptor pairs with different distances and orientations.[7] In the present case this composite decay could be well described by three mean lifetimes. It should be noticed that the longest luminescence lifetime of **1** is coincident with that of the Zn(II) model unit PZn (2.2 ns) and indicates that a fraction of peripheral donors remain unquenched. This could be due to large distances between Zn(II) porphyrin donors and free-base porphyrin acceptors in extended conformations, which could prevent the energy transfer from competing with the intrinsic deactivation of the donor excited state.[8] Further studies to determine the detailed mechanisms of the photo-induced processes in **1** are in progress.

In summary, a nona-porphyrin constituted of eight Zn(II) porphyrins anchored to a tetra-nucleosidic free-base porphyrin has been synthesized for its light absorbance capability and its ability to deliver this energy to the central chromophore. Photo-physical studies highlighted the existence of several conformations resulting in various donor–acceptor pairs with different distances and orientations, as well as an efficient energy transfer from the Zn(II) peripheral porphyrins to the free-base core for the non-extended conformers bearing face-to-face chromophores. The enantio-pure nucleosidic linkers generate a chiral spatial arrangement of the porphyrins, probably helical, and thus confer optical activity on this high molecular weight compound. Furthermore, one interest in the use of uridine linkers concerns the possibility of taking advantage of the hydrogen bonds that nucleic bases can establish with a complementary unit. It will thus be possible to extend our nona-porphyrin to bigger arrays, including a larger number of peripheral Zn(II) porphyrins, by self-assembling processes with complementary moieties functionalized with Zn(II) porphyrins.

Experimental

Uncorrected emission spectra in spectroscopic grade toluene solutions were detected by a Spex Fluorolog II spectrofluorimeter equipped with a Hamamatsu R928 photomultiplier. Luminescence lifetimes were determined by an apparatus based on a Nd:YAG laser (Continuum PY62-10) with a 35 ps pulse duration, 532 nm, 1 mJ/pulse and a Streak Camera (Hamamatsu C1587 equipped with M1952). Fitting of the luminescence decays was performed by standard iterative non linear programs taking into consideration the instrumental response.

Syntheses

Bis-porphyrin 3. Bis-porphyrin **2** (210 mg, 0.08 mmol, 1 eq.) is dissolved in dry DMF (5 ml). A 1 M solution of TBAF in THF (0.48 ml, 0.48 mmol, 6 eq.) is added and the reaction mixture is stirred for 7 h under inert atmosphere at room temperature. The DMF is then evaporated. The crude product is dissolved in CH_2Cl_2 and washed with distilled water. After evaporation of the solvent, the crude product is chromatographed over silica gel (AcOEt–hexane 80 : 20) and the desired compound is isolated in 94% yield (190 mg, 0.08 mmol).

3: Purple glassy product. ^{1}H-NMR (300 MHz, $CDCl_3$): δ 9,00 (s, 8H, H_β), 8.99 (d, 4H, H_β, ^3J = 5.6 Hz), 8.96 (d, 4H, H_β,

$^3J = 5.0$ Hz), 8.11 (d, 4H, H_o, $^3J = 8.6$ Hz), 8.09 (d, 8H, $H_{o'}$, $^4J = 2.0$ Hz), 8.08 (d, 4H, $H_{o''}$, $^4J = 2.4$ Hz), 7.78 (t, 6H, $H_{p,p'}$, $^4J = 1.8$ Hz), 7.23 (s, 2H, H_9), 7.18 (d, 4H, H_m, $^3J = 8.6$ Hz), 5.17 (s, 4H, H_7), 4.22 (t, 4H, $CH_2\gamma$, $^3J = 6.0$ Hz), 4.00 (t, 2H, H_1, $^3J = 6.0$ Hz), 2.68 (t, 4H, $CH_2\alpha$, $^3J = 7.1$ Hz), 2.68 (t, 2H, H_3, $^3J = 7.1$ Hz), 2.35 (s, 3H, CH_3), 2.25 (quin, 4H, $CH_2\beta$, $^3J = 6.6$ Hz), 2.21 (m, 2H, H_2, $^3J = 6.6$ and 7.7 Hz), 1.51 (s, 108H, ^{t}Bu). Elemental analysis for $C_{157}H_{178}N_8O_9Zn_2$: C, 76.9; H, 7.3; N, 4.6. Found: C, 75.3; H, 7.4; N, 4.5%.

Bis-porphyrinic precursor 5. Functionalized uridine **4** (22 mg, 0.05 mmol, 1.2 eq.) and DMAP (11 mg, 0.09 mmol, 2.2 eq.) are dissolved in CH_2Cl_2 stabilized with amylene (10 ml). Bis-porphyrin **3** (100 mg, 0.04 mmol, 1 eq.) and DCC (12 mg, 0.06 mmol, 1.5 eq.) are added and the reaction mixture is stirred for 7 h under inert atmosphere at room temperature. The solvent is then evaporated and the formed dicyclohexylurea is precipitated in toluene. After filtration over a glass frit, the toluene is evaporated. The crude product is chromatographed over silica gel (AcOEt–hexane 60 : 40) and the desired compound **5** is isolated with 50% yield (60 mg, 0.02 mmol).

5: Purple glassy product. ^{1}H-NMR (300 MHz, $CDCl_3$): δ 9.82 (s, 1H, CHO), 9.00 (s, 8H, H_β), 8.98 (d, 4H, H_β, $^3J = 5.0$ Hz), 8.96 (d, 4H, H_β, $^3J = 5.0$ Hz), 8.11 (d, 4H, Ho, $^3J = 8.9$ Hz), 8.10 (d, 4H, Ho″, $^4J = 1.5$ Hz), 8.09 (d, 8H, Ho′, $^4J = 1.8$ Hz), 7.78 (t, 6H, Hp,p′, $^4J = 1.8$ Hz), 7.65 (d, 2H, H_B, $^3J = 8.4$ Hz), 7.48 (d, 2H, H_A, $^3J = 8.2$ Hz), 7.49 (s, 1H, H_6), 7.27 (s, 2H, H_9), 7.20 (d, 4H, H_m, $^3J = 8.8$ Hz), 5.35 (d, 1H, $H_{1'}$, $^3J = 4.2$ Hz), 5.23 (t, 1H, $H_{3'}$, $^3J = 5.7$ Hz), 5.20 (t, 1H, $H_{2'}$, $^3J = 4.8$ Hz), 5.16 (s, 4H, H_7), 4.25 (t, 4H, $CH_{2\gamma}$, $^3J = 6.0$ Hz), 4.10 (dd, 2H, $H_{5'}$, $^3J = 3.3$ and 12.6 Hz), 3.94 (m, 1H, $H_{4'}$), 3.92 (t, 2H, H_1, $^3J = 6.0$ Hz), 2.75 (t, 4H, $CH_{2\alpha}$, $^3J = 7.3$ Hz), 2.72 (t, 2H, H_3, $^3J = 7.7$ Hz), 2.37 (s, 3H, CH_3), 2.28 (m, 4H, $CH_{2\beta}$, $^3J = 6.0$ and 7.0 Hz), 2.16 (quin, 2H, H_2, $^3J = 6.0$ Hz), 2.00 (s, 3H, CH_3 OAc), 1.98 (s, 3H, CH_3 OAc), 1.52 (s, 72H, tBu′), 1.50 (s, 36H, tBu). Elemental analysis for $C_{179}H_{196}N_{10}O_{17}Zn_2$: C, 74.3; H, 6.8; N, 4.8. Found: C, 73.0; H, 6.9; N, 4.8%.

Nonaporphyrin 1. Precursor **5** (250 mg, 0.086 mmol, 4 eq.) and pyrrole (6 µl, 0.086 mmol, 4 eq.) are dissolved in $CHCl_3$ (9 ml). A catalytic amount of a 3.2 M solution of $BF_3 \cdot OEt_2$ in $CHCl_3$ (9 µl, 0.029 mmol, 3.3×10^{-3} M) is added. The mixture is stirred at room temperature under inert atmosphere for 48 h. *p*-chloranil is then added (16 mg, 0.065 mmol, 3 eq.) and the mixture is stirred for 2 h 30 under reflux. NEt_3 is then added (8 µl, 0.029 mmol, 2.1 eq.) and the solvent evaporated. The crude mixture is chromatographed twice over silica gel (AcOEt –hexane 50 : 50 to AcOEt–MeOH 95 : 5). After a final size exclusion chromatography in toluene, the nonaporphyrin **1** is isolated in 35% yield (90 mg, 0.0076 mmol).

1: Brownish glassy product. MALDI-TOF MS: mass peak obtained upon addition of TFA and formation of the demetallated and protonated species: *m*/*z* 11251.1 (11251.8 calcd for $C_{732}H_{812}N_{44}O_{64}$). UV–VIS λ_{max} (CH_2Cl_2)/nm: 424 (3562000), 516 (61900), 552 (175000), 593 (78000), 649 (19400). Fluorescence: λ_{em} (CH_2Cl_2)/nm: 603, 651, 721 nm. Elemental analysis for $C_{732}H_{796}N_{44}O_{64}Zn_8 \cdot CH_2Cl_2$: C, 73.1; H, 6.7; N, 5.1. Found: C, 72.9; H, 6.9; N, 5.2%.

Acknowledgements

This work was supported by the CNRS and the French Ministry of Research (ACI Jeunes Chercheurs to N.S.), by the CNR of Italy (PM-P03-ISOF-M5) and MIUR (FIRB,RBNE019HNK). We thank the Region Guyane for a grant to C. S. H. H. thanks the International Research Training Group (GRK 532) for a PhD fellowship.

References

1 (*a*) J. Barber and B. Andersson, *Nature*, 1994, **370**, 31; (*b*) W. Kühlbrandt, *Nature*, 1995, **374**, 497; (*c*) G. McDermott, S. M. Prince, A. A. Freer, A. M. Hawthornthwaite-Lawless, M. Z. Papiz, R. J. Cogdell and N. W. Isaacs, *Nature*, 1995, **374**, 517; (*d*) T. Pullerits and V. Sundström, *Acc. Chem. Res.*, 1996, **29**, 381.

2 (*a*) S. Prathapan, T. E. Johnson and J. S. Lindsey, *J. Am. Chem. Soc.*, 1993, **115**, 7519; (*b*) C. Ching Mak, N. Bampos and J. K. M. Sanders, *Angew. Chem., Int. Ed.*, 1998, **37**, 3020; (*c*) M. Ravikanth, *Tetrahedron Lett.*, 2000, **41**, 3709; (*d*) R. A. Haycock, A. Yartsev, U. Michelsen, V. Sundström and C. A. Hunter, *Angew. Chem., Int. Ed.*, 2000, **39**, 3616; (*e*) M.–S. Choi, T. Aida, T. Yamazaki and I. Yamazaki, *Chem.–Eur. J.*, 2002, **8**, 2668; (*f*) M.-S. Choi, T. Yamazaki, I. Yamazaki and T. Aida, *Angew. Chem., Int. Ed.*, 2004, **43**, 150; (*g*) H. Himahori, *J. Phys. Chem. B*, 2004, **108**, 6130; (*h*) M. C. Lensen, S. J. T. van Dingenen, J. A. A. W. Elemans, H. P. Dijkstra, G. P. M. van Klink, G. van Koten, J. W. Gerritsen, S. Speller, R. J. M. Nolte and A. E. Rowan, *Chem. Commun.*, 2004, **762**; (*i*) D. Kim and A. Osuka, *Acc. Chem. Res.*, 2004, **37**, 735.

3 N. Solladié, M. Gross, J.-P. Gisselbrecht and C. Sooambar, *Chem. Commun.*, 2001, 2206.

4 For examples of nucleotide–porphyrin conjugates, see: (*a*) N. Solladié and M. Gross, *Tetrahedron Lett.*, 1999, **40**, 3359; (*b*) S. Masiero, G. Gottarelli and S. Pieraccini, *Chem. Commun.*, 2000, 1995; (*c*) J. L. Sessler, J. Jayawickramarajah, A. Gouloumis, T. Torres, D. M. Guldi, S. Maldonado and K. J. Stevenson, *Chem. Commun.*, 2005, 1892.

5 (*a*) J. S. Lindsey, I. C. Schreiman, H. C. Hsu, P. C. Kearney and A. M. Marguerettaz, *J. Org. Chem.*, 1987, **52**, 827; (*b*) J. S. Lindsey and R. W. Wagner, *J. Org. Chem.*, 1989, **54**, 828.

6 (*a*) T. Kurtan, N. Nesnas, F. E. Koehn, Y.-Q. Li, K. Nakanishi and N. Berova, *J. Am. Chem. Soc.*, 2001, **123**, 5974; (*b*) V. V. Borovkov, J. M. Lintuluoto and Y. Inoue, *J. Am. Chem. Soc.*, 2001, **123**, 2979.

7 See for example: (*a*) A. Nakano, A. Osuka, I. Yamazaki, T. Yamazaki and Y. Nishimura, *Angew. Chem., Int. Ed.*, 1998, **37**, 3023; (*b*) M. S. Choi, T. Aida, T. Yamazaki and I. Yamazaki, *Chem.–Eur. J.*, 2002, **8**, 2668; (*c*) L. Flamigni, A. M. Talarico, B. Ventura, G. Marconi, C. Sooambar and N. Solladie, *Eur. J. Inorg. Chem.*, 2004, 2557.

8 Th. Förster, *Discuss. Faraday Soc.*, 1959, **27**, 7.