ChemPubSoc Europe

DOI: 10.1002/chem.201704903

CHEMISTRY
A European Journal
Full Paper

Radical Reactions

Revisiting the Ullman's Radical Chemistry for Phthalocyanine Derivatives

Ismail Fidan,[a] Dominique Luneau,[b] Vefa Ahsen,*[a] and Catherine Hirel*[a]

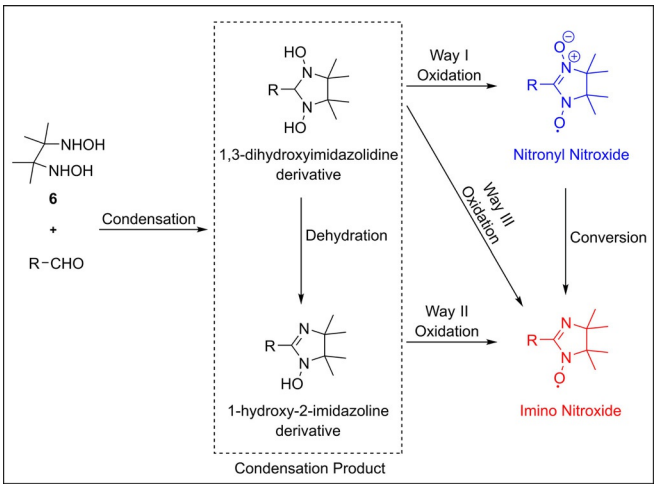
Dedicated to the memory of Paul Rey

Abstract: Phthalocyanine derivatives do not cease to gain attention due to their numerous properties and applications (e.g., sensor, PDT). This makes them a unique scaffold for the design of new material. In this context, we were interested to develop the synthesis of an imino nitroxide-substituted phthalocyanine by Ullman's procedure; a challenge due to the intrinsic low solubility of most phthalocyanine derivative in much solvents. To overcome this solubility problem, we designed a phthalocyanine with bulky neopentyl substituents in peripheral positions as counterpart to the imino nitroxide moieties. The imino nitroxide-substituted phthalocyanine was obtained by condensation of a monoformyl-substituted phthalocyanine with 2,3-bis(hydroxylamino)-2,3-dimethylbutane in refluxing THF–MeOH (2:1) mixture in the presence of *p*-toluenesulfonic acid monohydrate, follow by oxidation with PbO_2. Characterization was performed by electrochemistry, UV/Vis and EPR spectroscopy in solution as well as SQUID in solid state.

Introduction

Among open-shell molecules, imino and nitronyl nitroxide free-radical derivatives are one of the most represented compound families due to their high stability and versatile synthesis. They have been essentially famous as building blocks in magnetic materials.[1,2] A renewed interest in their chemistry has come in the spotlight because of their involvement in organic electrode-active materials[3] or fluorophore-nitroxide hybrid probe.[4] Imino and nitronyl nitroxide radical derivatives are classically obtained by the Ullman procedure,[5] involving the condensation of 2,3-bis(hydroxylamino)-2,3-dimethylbutane (**6**) with an appropriate aldehyde in methanol to generate the 1,3-dihydroxyimidazolidine derivative. For aromatic aldehydes, condensation takes hours at reflux. However, in some cases the reaction goes further and the 1,3-dihydroxyimidazolidine derivative undergoes dehydration to 1-hydroxy-2-imidazoline.[6] In very exceptional cases, dehydration takes place even at room temperature.[7] Condensation products suffer from low solubility. Consequently, their purification and characterization are always a difficult task and the Ullman's synthesis is generally continued without further purification. Oxidation of 1,3-dihydroxyimidazolidine or 1-hydroxy-2-imidazoline condensation product can be carried out by employing various oxidants such as $NaIO_4$, PbO_2, MnO_2, or even in air to afford the corresponding nitronyl nitroxides (Way I) and imino nitroxide (Way II). In case of excess of oxidant[8] or if the solution is acidic,[2] nitronyl nitroxides are converted spontaneously to imino nitroxide in a non-reversible way (Way III), as described in Scheme 1. Notably, the purity of 2,3-bis(hydroxylamino)-2,3-dimethylbutane (**6**) has a direct impact on the success.[9]

Although imino and nitronyl nitroxide free-radical derivatives are obtained satisfactorily with numerous substituents, the Ullman route suffers from major drawbacks in the case of



Scheme 1. Syntheses of nitronyl nitroxide and imino nitroxide free-radicals.

[a] Dr. I. Fidan, Prof. V. Ahsen, Dr. C. Hirel
Department of Chemistry, Gebze Technical University
Faculty of Science, Gebze, 41400 Kocaeli (Turkey)
E-mail: ahsen@gtu.edu.tr
chirel@gtu.edu.tr

[b] Prof. D. Luneau
Université Claude Bernard Lyon 1
Laboratoire des Multimatériaux et Interfaces (UMR 5615)
Campus de La Doua, 69622 Villeurbanne Cedex (France)

Supporting information and the ORCID number(s) for the author(s) of this article can be found under https://doi.org/10.1002/chem.201704903.

© 2018 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

highly aromatic aldehyde which require multi-step synthesis. Their low solubility in methanol as well as the stabilization of the aldehyde function by resonance prevents the condensation with **6** in an appropriate manner. Despite these constraints, the Ullman radicals were introduced in numerous molecules like pyrene,[10] quinoline,[11] 1,2,4-triazole,[12] calixarene[13] or ferrocene[14] or even in the axial position of tetraphenylporphinatozinc(II) coordinated by *p*-pyridyl nitronyl nitroxide.[15]

Our interest in the phthalocyanine dyes as a promising group of fluorophore derivatives with high quantum yield, used in numerous applications (chemical sensor, solar cell, PDT, etc.), prompted us to investigate the synthesis of a phthalocyanine covalently linked to an imino nitroxide moiety. This has been a real challenge and motivation to revisit the Ullman's radical chemistry owing to the low solubility of the phthalocyanines. There are synthetic problems at each step that need to be specifically taken with care and to carefully consider: i) obtain the key precursor 2,3-bis(hydroxylamino)-2,3-dimethylbutane (**6**); (ii) formyl-substituted phthalocyanine in pure and good yield; and iii) optimize the condensation and the oxidation step conditions in an efficient way. These issues are probably the cause of the lack of phthalocyanines bearing Ullman's radical. Step i) was not a problem for us as the synthesis of **6** has been for a long time mastered in our laboratory. Step ii) and iii) required reconsideration.

To have an acceptable solubility, we restricted our investigation to a mono imino nitroxide-substituted phthalocyanine and ancillary bulky neopentyl substituents on other peripheral positions. Synthesis of the mono formyl-substituted phthalocyanine was thus a prerequisite. In the literature, there are only few reports about monoformyl-substituted phthalocyanine based on two strategies: post-modification of a preformed macrocycles to introduce formyl group or protection of the formyl group at the phthalonitrile level. By the former method, formyl group is obtained by oxidative cleavage reaction of the monovinyl-substituted phthalocyanine[16] or oxidation of hydroxymethyl-substituted phthalocyanine.[17,18] As the formyl group is fragile and will not withstand the harsh Rosenmund–von Braun cyanation or phthalocyanine formation conditions, its protection is indispensable. Indeed, cyanation by Rosenmund–von Braun takes place at elevated temperatures which may lead to decomposition of aldehyde. To be on the safe side, aldehyde group was protected prior to cyanation process. Ethylene glycol was reported to protect the formyl function to form a dioxalane derivative that is easily deprotected after phthalocyanine formation by cleavage with 2 N hydrochloric acid in THF at room temperature.

In this article, we describe the first synthesis of a metal-free phthalocyanine macrocycle bearing one imino nitroxide radical as substituent (**10**) which has been fully characterized (see Scheme 2). This comprises an alternative synthesis to monoformyl-substituted phthalocyanine by the protection/deprotection pathway and a detail optimization of the key steps aforementioned condensation and oxidation for the imino nitroxide formation.

Results and Discussion

The monoformyl phthalocyanine

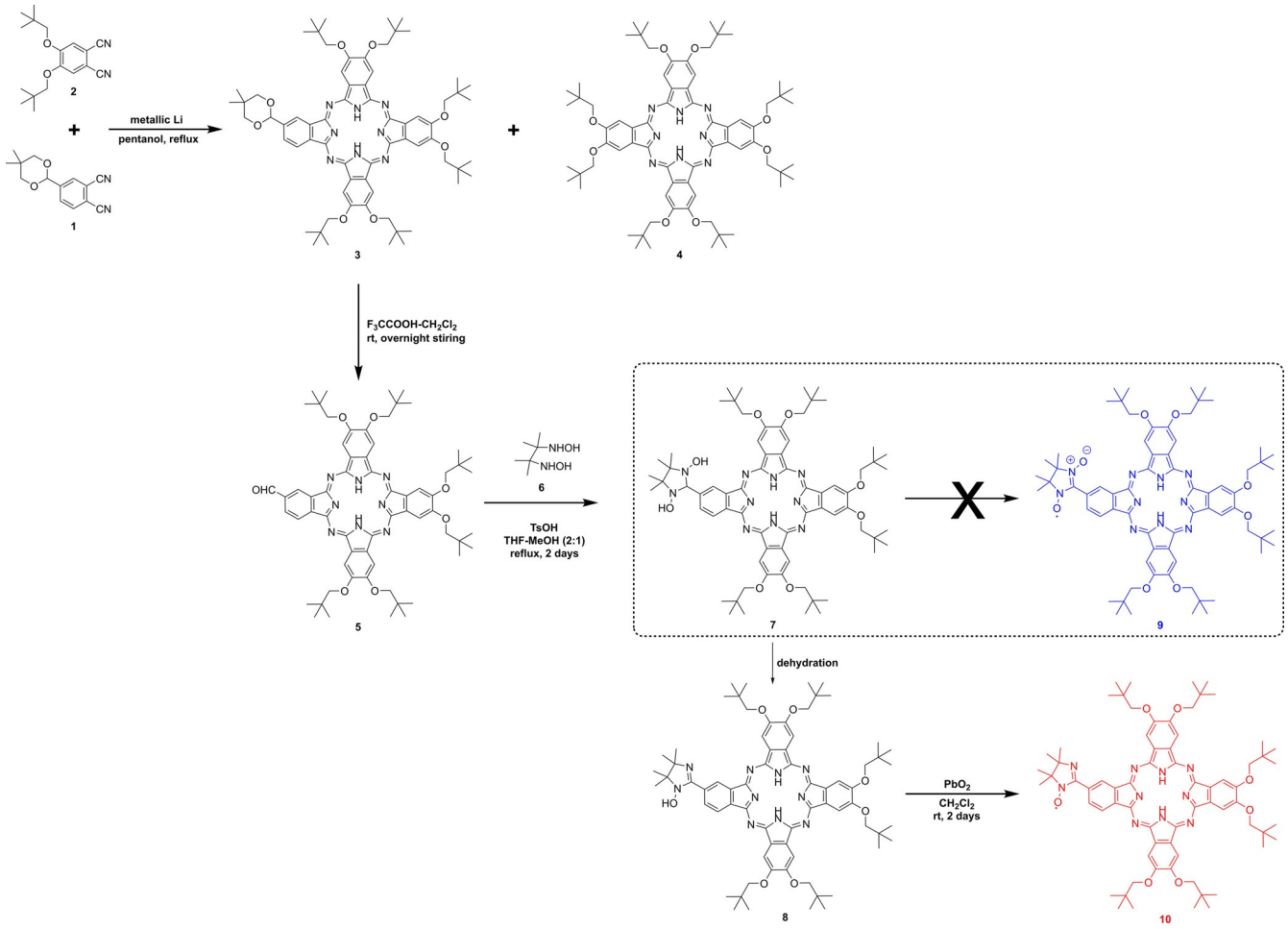
As stated above, our strategy to obtain a phthalocyanine bearing one imino nitroxide radical (**10**) is based on the Ullman's route, the unavoidable precursor of which should be a formyl group. Therefore, we sought to synthesize an asymmetric A_3B-type phthalocyanine bearing in one hand a protected formyl group and on the other hand neopentyl bulky group substituents at the peripheral positions (**5**) to reduce aggregation and increase the solubility in organic solvents. A_3B-type phthalocyanine classical synthetic methodology consists of the statistically crossover condensation[19] of two appropriate phthalonitrile precursors in different ratio; in our case 4,5-dineopentoxyphthalonitrile (**2**) and 4-(5,5-dimethyl-1,3-dioxane-2-yl)-phthalonitrile (**1**). The synthesis of phthalonitrile **2** was carried out on the basis of Leznoff's procedure[20] with substantial modifications (Scheme S1 in the Supporting Information). Catechol was brominated first,[21] in which1,2-dibromo-4,5-dihydroxybenzene was treated with hexamethylphosphoramide, KOH, tetraheptylammonium bromide, and neopentyl tosylate to give 1,2-dibromo-4,5-dineopentoxybenzene. The conversion of it to **2** was achieved by the Rosenmund–von Braun reaction under microwave irradiation in *N*-methyl-2-pyrrolidone (NMP) which makes possible to obtain a cleaner product with a better yield in a shorter time.[22] The synthesis of **1** is inspired by the procedure of Hanack's, only by modifying the nature of the protecting group.[23] 2,2-Dimethylpropan-1,3-diol, a vicinal diol that could be used without further purification, was preferred to ethylene glycol due to its ease of handling (Scheme S1). **3** was obtained by overnight reflux of **2** and **1** in pentanol under template effect of metallic lithium, in the ratio 6:1 to afford the mixture of the symmetric 2,3,9,10,16,17,23,24-octaneopentoxyphthalocyanine (**4**) and the asymmetric **3** in 23% yield, which have been isolated easily through column chromatography on silica gel eluting with dichloromethane-hexane mixture (Scheme 2). **3** and **4** were identified by MALDI-TOF mass spectroscopy, which show $[M+H]^+$ ion peaks at $m/z=1204$ and $m/z=1146$, respectively (Figures S18, S20 in the Supporting Information).

The cleavage of the dioxalane group performed in F_3CCOOH-CH_2Cl_2 (1/1) mixture at room temperature provides **5** almost quantitatively (Scheme 2). Characterization of **5** is provided in Figures S21–24 in the Supporting Information. The FT-IR showed the typical carbonyl stretching of aldehyde at 1693 cm^{-1}, the characteristic formyl resonance at $\delta=10.40$ ppm in the ^1H NMR and this was corroborated by the ion peak at $m/z=1060$ $[M+H]^+$. The production of **5** in sufficient quantity is important to guarantee the optimization work required during the following condensation and oxidation steps.

Condensation optimization

The condensation step between **6** and aldehyde derivative is classically carried out by refluxing them in methanol. The use of methanol is a crucial parameter because **6** is very soluble in

© 2018 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim



Scheme 2. The Ullman's synthetic route to metal-free phthalocyanine macrocycle bearing one imino nitroxide radical as a substituent (**10**).

it and it acts also as a catalyst by its slight acidity. But this could be also a major drawback when aldehydes are not or only partially soluble in it. In these cases, the condensation conditions need to be addressed specifically. A co-solvent may be required to overcome the aldehyde solubility obstacle[24] or an alternative catalyst like toluenesulfonic acid (TsOH) in high boiling point solvent may force the condensation reaction.[25] Solvent free condensation[26] is also one possibility even if it is seldomly used in the literature. Table 1 reports the experimental condensation reaction conditions tested due to the lack of solubility of **5** in methanol. The best condensation conditions for the phthalocyanine derivative were observed in refluxing THF–MeOH (2:1) mixture over two days in the presence of TsOH. On this basis, solely 1-hydroxy-2-imidazoline derivative (**8**) instead of the anticipated 1,3-dihydroxyimidazolidine derivative (**7**) was obtained as confirmed by MALDI-TOF mass spectroscopys which presents an ion peak at $m/z = 1171$ $[M]^+$ (Figure S26 in the Supporting Information).

The dehydration of **7** seems to be promoted not only by high reflux temperature but also combined with the use of an excess of TsOH. Further optimizations are still in progress to find the balance of the TsOH ratio which may give accessibility to **7**. Taking these facts into account, solely imino nitroxide-substituted phthalocyanine **10** could be accessed by the oxidation.

Oxidation optimization

MnO_2, PbO_2, $NaIO_4$, or bubbling of the air in a NH_4OH (aq.)/ MeOH/ $Cu(OAc)_2$ mixture are among the common oxidants utilized in the Ullman pathway. Each oxidation conditions were tested to find the best oxidative conditions. The suspension of an excess of MnO_2[27] or PbO_2[28] in solvent like CH_2Cl_2, $CHCl_3$ or toluene leads to a heterogeneous oxidation, whereas oxidation by a drop-wise addition of $NaIO_4$ (aq.) requires a bi-phasic solution of a water-immiscible solvent such as CH_2Cl_2 or diethyl ether and saturated $NaHCO_3$ (aq.) solution to be vigorously stirred.[2] Bubbling of air into a NH_4OH (aq.)/MeOH/ $Cu(OAc)_2$ mixture was less common. The experiments achieved were tabulated in Table 2.

The oxidation of **8** was achieved efficiently only by the use of PbO_2 in CH_2Cl_2 at room temperature. After two days of stirring at RT, a green solution corresponding to the imino nitroxide-substituted phthalocyanine derivative **10** was obtained and isolated as a green solid in 38% yield (Scheme 2). **10** was characterized unambiguously with a rich array of analyses such

© 2018 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

Table 1. Optimization of condensation reaction conditions.[a]

Entry	Solvent	*T*	Additive	*t* [days]	Result
1	CH_2Cl_2–MeOH (2:1)	RT	–	7	no reaction
2[a]	CH_2Cl_2–MeOH (2:1)	RT	TsOH	7	no reaction
3[a]	CH_2Cl_2–MeOH (2:1)	reflux	TsOH	3	no reaction
4[a]	PhMe–MeOH (2:1)	RT	TsOH	7	no reaction
5[a]	PhMe–MeOH (2:1)	reflux	TsOH	3	small amount formed but not complete
6	THF–MeOH (2:1)	RT	–	7	no reaction
7[b]	THF–MeOH (2:1)	RT	TsOH	7	no reaction
8	THF–MeOH (2:1)	50 °C	–	7	no reaction
9[b]	THF–MeOH (2:1)	50 °C	TsOH	7	small amount formed but not complete
10[b]	THF–MeOH (2:1)	reflux	TsOH	2	product formed
11	solvent free	RT	–	7	no reaction
12[b]	solvent free	RT	TsOH	7	no reaction

[a] General optimization reaction conditions: Monoformyl-substituted phthalocyanine (**5**) (10.7 mg, 1 equiv) and **6** (14.8 mg, 10 equiv) were stirred in 2 mL of methanol and 4 mL of co-solvent under argon atmosphere. Progress of the reaction was monitored by TLC analysis. [b] 6 equiv of TsOH (11.4 mg, 6 equiv) were added.

Table 2. Optimization of oxidation conditions.[a]

Entry	Oxidant	Solvent	*t* [days]	Result
1[b]	$NaIO_4$	CH_2Cl_2–$NaHCO_{3(aq.)}$	3	reaction did not run to completion
2[c]	PbO_2	CH_2Cl_2	2	**8** is completely consumed; product formed
3[d]	MnO_2	CH_2Cl_2	2	phthalocyanine decomposed
4[e]	air	THF–MeOH, $NH_4OH_{(aq.)}$	3	reaction very slow, byproducts formed

[a] General optimization reaction conditions: **8** (11.7 mg, 1 equiv) was suspended in 30 mL of organic solvent. The mixtures were stirred vigorously at room temperature for 3 days in dark. Progress of the reaction was monitored by TLC. [b] Addition of saturated $NaHCO_{3(aq.)}$ solution (20 mL) and $NaIO_4$ (21.4 mg, 10 equiv) dissolved in H_2O (5 mL). [c] PbO_2 (480 mg, 200 equiv). [d] Activated MnO_2 (174 mg, 200 equiv). [e] $NH_4OH_{(aq.)}$ (10 mL) and $Cu(OAc)_2$ (catalytic amount) were added. Air was bubbled through the solution.

as FT-IR, MALDI-TOF MS, elemental analysis, UV/Vis, CV, EPR, demonstrating the strength and the universality of the Ullman method in obtaining nitroxide radicals, even with extreme solubility conditions.

UV/Vis spectroscopy

To gain first insight into electronic interactions between the radical and phthalocyanine moieties, the absorption and emission spectra of **4** and **10** were recorded in THF and presented in Figure 1. **4** and **10** were soluble in organic solvents such as DCM or THF in which the Beer–Lambert law was observed for both compounds in the range of 10^{-6} M to 10^{-5} M (Figures S29–S33, S54, S55 in the Supporting Information). **4** and **10** show the typical split Q band characteristic of free-based phthalocyanines.[20] In contrast, the low symmetry of **10** leads to closer Q bands. B bands around 350 nm are almost identical to each other. Noteworthy is that the extension of the conjugation pathway introduced by the imino nitroxide radical moiety of **10** (λ_{max} = 441 nm) leads to a 11 nm red shift of the charge transfer band in comparison to that of **4** (λ_{max} = 430 nm). In the visible range, the specific weak transitions of imino nitroxide radical at about 450 nm[7] are simply overshadowed by those of phthalocyanine. Both molecules exhibit one main fluorescence emission band at 699 nm, but as anticipated, the introduction of the radical moiety result in an 8-fold decrease of the fluorescence intensity. Fluorescence quantum yield in THF were found to be $\Phi_{F(4)}$ = 0.25 and $\Phi_{F(10)}$ = 0.03 for **4** and **10**, respectively, thus confirming the quenching of the fluorescence.

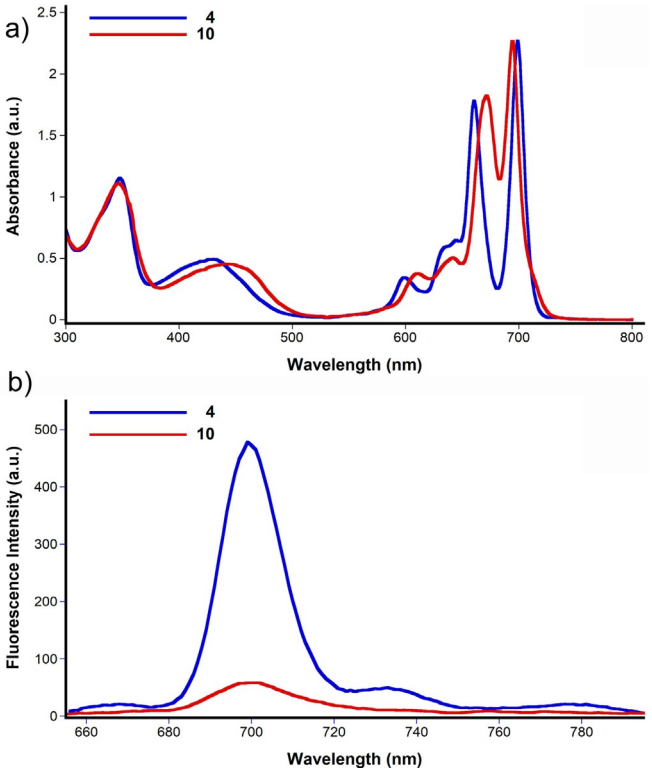


Figure 1. a) UV/Vis and b) fluorescence emission spectra of **4** and **10** in THF.

EPR spectroscopy

The typical seven-line splitting pattern with the relative intensity 1:1:2:1:2:1:1 presented in Figure 2, proves the radical existence of **10**. The seven-line spectrum was reasoned by the interaction of the unpaired electron (S = 1/2) with two unequivalent ^{14}N nitrogen atoms (nuclear spin I = 1) in the imidazoline ring. This spectrum was simulated with Jeol IsoSimu computer program. Best-fitting parameters are found as g = 2.0088, a_{N1} = 9.3 G, a_{N2} = 4.2 G, $\Delta H_{p\text{-}p}$ = 2.1 G.

© 2018 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

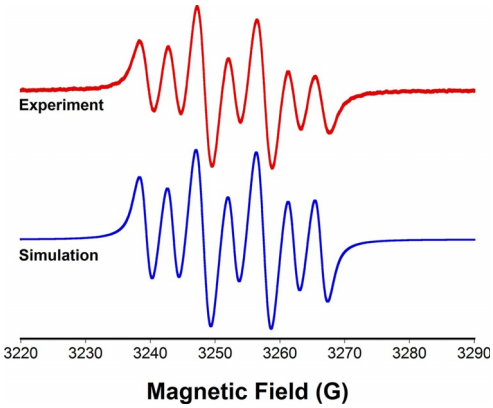


Figure 2. EPR Spectra of the radical **10** at 293 K at 10^{-4} M in dichloromethane–toluene (1:1) mixture.

Electrochemical measurements

The electrochemical behavior of imino nitroxide-substituted phthalocyanine **10** was investigated by cyclic voltammetry. **10** showed an irreversible oxidation wave at 1.260 V vs. SCE and a reversible reduction one at −0.886 V (see Figure 3). Noteworthy is that potentials were referenced to ferrocene/ferrocenium couple by taking $E_{1/2}$ (Fc/Fc^{+}) = 0.480 V vs. SCE in dichloromethane with 0.1 M nBu$_4$NClO$_4$ as supporting electrolyte.[29] The redox characteristics and the observed potentials is another way to demonstrate the radical character of imino nitroxide-substituted phthalocyanine **10**.

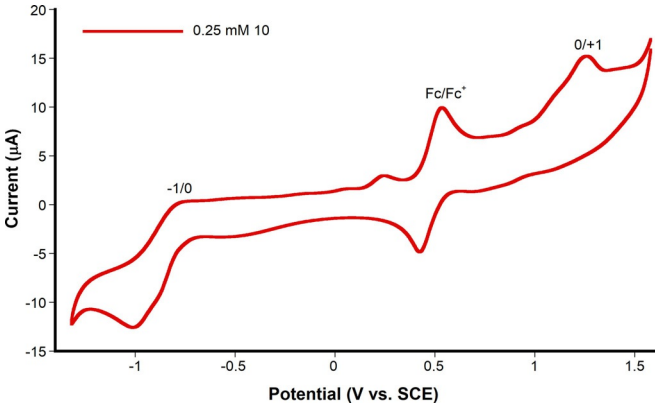


Figure 3. Cyclic voltammogram of phthalocyanine **10** recorded at RT in dichloromethane, 0.1 M nBu$_4$NClO$_4$ as supporting electrolyte, scan rate of 100 mV s^{-1}.

Magnetic study

The magnetic measurements that were performed on different samples have revealed that compound **10** is diamagnetic in the solid state. Thus, diamagnetism in the solid state can only be explained if strong intermolecular antiferromagnetic interactions are operative. Strong ferro- or antiferromagnetic intermolecular interactions between nitronyl or imino nitroxyde free radicals are not uncommon. They may occur either through a direct interaction between the N–O group[30] or a McConnell-type interaction.[31] In the present case, a McConnell-type interaction is unlikely as it requires that the phenyl groups bearing the radical come close in a stacking mode, which is sterically prevented by the bulky neopenthyl substituents. We favor a direct interaction of the N–O group in a head-to-tail mode (Figure 4) that generally results in strong antiferromagnetic interaction and a diamagnetic behavior as is observed here for **10**.

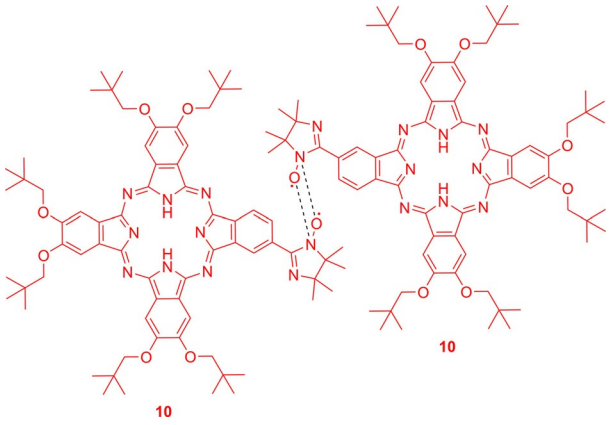


Figure 4. Representation of N–O group in a head-to-tail mode.

Conclusion

An imino nitroxide radical moiety covalently bonded to phthalocyanine macrocycle was successfully synthesized for the first time in spite of the inherent phthalocyanine problems, that is, high aromaticity and insolubility in methanol, which prevents condensation with 2,3-bis(hydroxylamino)-2,3-dimethylbutane. The use of a co-solvent associating with TsOH as catalyst in the condensation step and PbO_2 as oxidant were the best conditions. **10** was obtained in good yield according to the multistep synthesis. As expected, the fluorescence intensity and the quantum yield of **10** were very low compared to the symmetrical counterpart **4**. The potential of this new optimized pathway is promising for the synthesis of novel highly aromatic nitroxides. Especially, fluorophore linked to nitroxide is a promising candidate for sensor applications based principally on the OFF–ON principle.

Experimental Section

The synthetic procedures for **1**, **2**, and **6** are provided in the Supporting Information.

2-(5,5-Dimethyl-1,3-dioxane-2-yl)-9,10,16,17,23,24-hexaneopentoxyphthalocyanine (3): Metallic lithium was dissolved in pentanol (50 mL) and stirred for 1 hour. Phthalonitrile **1** (1 equiv, 0.002 mol, 0.484 g) and phthalonitrile **2** (6 equiv, 0.012 mol, 3.600 g) were added to the solution and refluxed overnight. The intense green solution was cooled to ambient temperature and added drop by drop into water-ethanol mixture to form a green precipitate, which was collected by suction filtration, washed with water and ethanol, to be finally dried under air stream to afford 3.800 g of a crude

© 2018 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

green waxy solid. Crude product was purified by column chromatography on silica gel eluting with dichloromethane–hexane mixture. Column purification gave two major products; 1.680 g of the symmetric 2,3,9,10,16,17,23,24-octaneopentoxyphthalocyanine (**4**) as a green waxy solid and 0.527 g of asymmetric **3** as green powder in 23% yield.

Phthalocyanine **4**: FT-IR (ATR, ν_{max}, cm^{-1}) : 3295w, 3077w, 2954 s, 2906 s, 2867 m, 1600 m, 1491 s, 1465 s, 1444 s, 1419 m, 1391 s, 1362 s, 1325 s, 1275 s, 1260 s, 1211 s, 1197 s, 1170 m, 1098 s, 1053 s, 1014 s, 917 m, 866 s, 852 s, 806 s, 748 s, 723 m, 709 s, 693 m. MALDI-TOF MS (2,5-dihydroxybenzoic acid): *m/z* calcd for $C_{72}H_{98}N_8O_8$: 1203; found: 1204 $[M+H]^+$.

Phthalocyanine **3**: FT-IR (ATR, ν_{max}, cm^{-1}) : 3296w, 3032w, 2956 m, 2914 m, 2869 m, 1546 s, 1534 s, 1471 s, 1454 s, 1408 s, 1394 s, 1378 s, 1340 s, 1280 m, 1261 s, 1218 m, 1170 s, 1133 s, 1096 s, 1050 m, 1018 s, 850 s, 799 s, 766 s, 742 s, 647 m. MALDI-TOF MS (2,5-dihydroxybenzoic acid): *m/z* calcd for $C_{68}H_{88}N_8O_8$: 1145; found: 1146 $[M+H]^+$.

2-(Formyl)-9,10,16,17,23,24-hexaneopentoxyphthalocyanine (5): **3** (0.46 mmol, 0.527 g) was stirred in F_3CCOOH-CH_2Cl_2 mixture (40 mL-40 mL) at room temperature overnight. Green mixture was poured into water. The organic phase was extracted and washed with saturated $NaHCO_3$ (aq.) solution (5×100 mL), then with water (10×100 mL), to be finally dried over Na_2SO_4. Crude product was purified by column chromatography on silica gel eluting with dichloromethane-hexane mixture (5:1). Column purification gave 0.477 g of **5** as green powder in 98% yield. FT-IR (ATR, ν_{max}, cm^{-1}) : 3296w, 3077w, 2954 s, 2907 m, 2868 m, 1693 s, 1607 m, 1583 m, 1490 s, 1474 s, 1450 s, 1393 s, 1363 s, 1342 s, 1280 m, 1260 s, 1235 s, 1205 s, 1158 s, 1132 m, 1095 s, 1068 s, 1049 s, 1017 s, 921 s, 854 s, 830 s, 739 s, 715 s, 691 s; ^{1}H NMR (500 MHz, $CDCl_3$, ppm): $\delta=$ 10.40 (s, 1H, -CHO), 8.93 (s, 1H, aromatic -CH), 8.53 (d, $J=5$ Hz, 1H, aromatic -CH), 8.41 (s, 1H, aromatic -CH), 8.29 (s, 1H, aromatic -CH), 8.10 (m, 2H, aromatic -CH), 7.96 (s, 1H, aromatic -CH), 7.56 (m, 2H, aromatic -CH), 4.33 (s, 2H, -CH_2O-), 4.31 (s, 2H, -CH_2O-), 4.20 (s, 2H, -CH_2O-), 4.07 (s, 2H, -CH_2O-), 3.92 (s, 2H, -CH_2O-), 3.90 (s, 2H, -CH_2O-), 1.48 (s, 18H, neopentyl -CH_3), 1.45 (s, 9H, neopentyl -CH_3), 1.41 (s, 9H, neopentyl -CH_3), 1.38 (s, 18H, neopentyl -CH_3), −3.92 ppm (s, 2H, -NH); ^{13}C NMR (125 MHz, $CDCl_3$): $\delta=$192.79, 152.66, 152.48, 152.28, 152.22, 151.96, 151.93, 141.99, 137.96, 135.69, 133.20, 133.16, 129.46, 126.93, 126.72, 126.06, 126.01, 123.05, 122.21, 106.08, 105.96, 103.75, 103.54, 102.62, 102.45, 79.14, 78.83, 78.75, 78.49, 78.48, 77.73, 32.76, 32.63, 32.56, 32.53, 27.35, 27.29, 27.19 ppm; MALDI-TOF MS (2,5-dihydroxybenzoic acid): *m/z* calcd for $C_{63}H_{78}N_8O_7$: 1059; found: 1060 $[M+H]^+$ elemental analysis calcd (%) for $C_{63}H_{78}N_8O_7$: C 71.43, H 7.42, N 10.58; found: C 69.81, H 7.78, N 9.23.

2-(1-Oxyl-4,4,5,5-tetramethyl-2-imidazoline-2-yl)-9,10,16,-17,23,24-hexaneopentoxyphthalocyanine (10): **5** (1 equiv, 0.075 mmol, 0.079 g), 2,3-bis(hydroxylamino)-2,3-dimethylbutane (**6**) (40 equiv, 3 mmol, 0.444 g), and TsOH (6 equiv, 0.45 mmol, 0.086 g) were charged into 25 mL flask. The reaction solution was refluxed at 70 °C under argon in a THF (10 mL) and MeOH (5 mL) mixture for two days. The reaction mixture was evaporated to dryness. The green residue was dissolved in CH_2Cl_2 (150 mL) and washed firstly with 10% ethanol-water mixture (2×100 mL), then with saturated $NaHCO_3$ (aq.) solution (1×100 mL), finally with water (3×100 mL) and then dried over Na_2SO_4, evaporated to dryness under vacuum to give a green powder. FT-IR and MALDI-TOF MS analyses of the green powder (as crude product) confirmed the identity of **8** as 2-(1-hydroxy-4,4,5,5-tetramethyl-2-imidazoline-2-yl)-9,10,16,17,23,24-hexaneopentoxyphthalocyanine. FT-IR (ATR, ν_{max}, cm^{-1}) of compound **8**: 3296w, 3081w, 2954 s, 2907 m, 2868 m, 1607 m, 1488 s, 1474 s, 1451 s, 1393 s, 1363 s, 1329 s, 1279 s, 1260 s, 1208 s, 1173 s, 1096 s, 1047 s, 1015 s, 920 s, 855 s, 811 m, 788 m, 742 s, 716 s, 698 s; MALDI-TOF MS (*trans*-2-[3-(4-*tert*-butylphenyl)-2-methyl-2-propenylidene]-malononitrile): *m/z* calcd for $C_{69}H_{90}N_{10}O_7$: 1171; found: 1171 $[M]^+$.

The crude product of **8** was subjected to PbO_2 oxidation without further purification. **8** was suspended in CH_2Cl_2 (250 mL) in 1 L flask and PbO_2 (200 equiv, 3.6 g) was added as a suspension. The mixture was stirred vigorously at room temperature for 3 days in the dark. It was filtered on Celite-plug and washed with CH_2Cl_2. The green solution was evaporated to dryness. Crude product was purified with plaque chromatography on silica gel eluting with dichloromethane-methanol mixture (200:1). The plaque purification gave 0.033 g of **10** as green powder in 38% yield (from aldehyde). FT-IR (ATR, ν_{max}, cm^{-1}): 3296w, 3081w, 2955 s, 2925 m, 2867 m, 1736w, 1608w, 1491 s, 1474 s, 1451 s, 1393 s, 1363 s, 1329 m, 1279 s, 1260 s, 1209 m, 1171 s, 1097 s, 1049 s, 1016 s, 920 m, 873 s, 855 s, 796 s, 743 s, 717 s, 698 s; MALDI-TOF MS (*trans*-2-[3-(4-*tert*-butylphenyl)-2-methyl-2-propenylidene]-malononitrile): *m/z* calcd for $C_{69}H_{89}N_{10}O_7$: 1170; found: 1171 $[M+H]^+$; elemental analysis calcd (%) for $C_{69}H_{89}N_{10}O_7$: C 70.80, H 7.66, N 11.97; found: C 71.70, H 7.98, N 11.62.

Acknowledgements

The authors acknowledge the Scientific and Technical Research Council of Turkey (TÜBİTAK) through the project 114Z767 and the COST action CM1305 "ECOSTBio" for their financial support.

Conflict of interest

The authors declare no conflict of interest.

Keywords: dehydration · formyl-substituted phthalocyanine · imino nitroxide · radical · Ullman's synthesis

[1] V. Ovcharenko, *Metal–Nitroxide Complexes: Synthesis and Magnetostructural Correlations.In Stable Radicals: Fundamentals and Applied Aspects of Odd-Electron Compounds* (Ed.: R. G. Hicks), Wiley, Chichester, **2010**, Chapter 13, pp. 461–506.
[2] D. Luneau, P. Rey, *Coord. Chem. Rev.* **2005**, *249*, 2591–2611.
[3] T. Sukegawa, A. Kai, K. Oyaizu, H. Nishide, *Macromolecules* **2013**, *46*, 1361–1367.
[4] Y. B. Borozdina, V. Kamm, F. Laquaib, M Baumgarten, *J. Mater. Chem.* **2012**, *22*, 13260–13267.
[5] E. F. Ullman, J. H. Osiecki, D. G. B. Boocock, R. Darcy, *J. Am. Chem. Soc.* **1972**, *94*, 7049–7059.
[6] G. Zoppellaro, A. Geies, V. Enkelmann, M. Baumgarten, *Eur. J. Org. Chem.* **2004**, 2367–2374.
[7] I. Fidan, E. Onal, Y. Yerli, D. Luneau, V. Ahsen, C. Hirel, *Inorg. Chem.* **2016**, *55*, 11447–11453.
[8] G. Zoppellaro, A. Ivanova, V. Enkelmann, A. Geies, M. Baumgarten, *Polyhedron* **2003**, *22*, 2099–2110.
[9] C. Hirel, K. E. Vostrikova, J. Pecaut, V. I. Ovcharenko, P. Rey, *Chem. Eur. J.* **2001**, *7*, 2007–2014.
[10] H. Han, M. Wang, H. Wang, *New J. Chem.* **2014**, *38*, 914–917.
[11] E. V. Tretyakov, V. F. Plyusnin, A. O. Suvorova, S. V. Larionov, S. A. Popov, O. V. Antonova, E. M. Zueva, D. V. Stass, A. S. Bogomyakov, G. V. Romanenko, V. I. Ovcharenko, *J. of Luminescence* **2014**, *148*, 33–38.
[12] Y. Pei, O. Kahn, M. A. Aebersold, L. Ouahab, F. Le Berre, L. Pardi, J. L. Tholence, *Adv. Mater.* **1994**, *6*, 681–683.
[13] A. Rajca, M. Pink, S. Mukherjee, S. Rajca, K. Das, *Tetrahedron* **2007**, *63*, 10731–10742.

© 2018 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

[14] O. Jürgens, J. Vidal-Gancedo, C. Rovira, K. Wurst, C. Sporer, B. Bildstein, H. Schottenberger, P. Jaitner, J. Veciana, *Inorg. Chem.* **1998**, *37*, 4547 – 4558.
[15] K. Ishii, J. Fujisawa, Y. Ohba, S. Yamauchi, *J. Am. Chem. Soc.* **1996**, *118*, 13079 – 13080.
[16] A. Gouloumis, S.-G. Liu, Á. Sastre, P. Vázquez, L. Echegoyen, T. Torres, *Chem. Eur. J.* **2000**, *6*, 3600 – 3607.
[17] D. M. Guldi, A. Gouloumis, P. Vázquez, T. Torres, V. Georgakilas, M. Prato, *J. Am. Chem. Soc.* **2005**, *127*, 5811 – 5813.
[18] R. F. Enes, J.-J. Cid, A. Hausmann, O. Trukhina, A. Gouloumis, P. Vázquez, J. A. S. Cavaleiro, A. C. Tomé, D. M. Guldi, T. Torres, *Chem. Eur. J.* **2012**, *18*, 1727 – 1736.
[19] V. N. Nemykin, S. V. Dudkin, F. Dumoulin, C. Hirel, A. G. Gürek, V. Ahsen, *ARKIVOC* **2014**, *1*, 142 – 204.
[20] A. K. Khanamiryan, N. Bhardwa, C. C. Leznoff, *J. Porphyrins Phthalocyanines* **2000**, *4*, 484 – 490.
[21] M. Hu, N. Brasseur, S. Z. Yildiz, J. E. van Lier, C. C. Leznoff, *J. Med. Chem.* **1998**, *41*, 1789 – 1802.
[22] E. Önal, F. Dumoulin, C. Hirel, *J. Porphyrins Phthalocyanines* **2009**, *13*, 702 – 711.
[23] K.-H. Schweikart, M. Hanack, *Eur. J. Org. Chem.* **2000**, 2551 – 2556.
[24] A. Shimizu, A. Ito, Y. Teki, *Chem. Commun.* **2016**, *52*, 2889 – 2892.
[25] M. Minguet, D. Luneau, E. Lhotel, V. Vilar, C. Paulsen, D. B. Amabilino, J. Veciana, *Angew. Chem. Int. Ed.* **2002**, *41*, 586 – 589; *Angew. Chem.* **2002**, *114*, 606 – 609.
[26] S. Shimono, R. Tamura, N. Ikuma, T. Takimoto, N. Kawame, O. Tamada, N. Sakai, H. Matsuura, J. Yamauchi, *J. Org. Chem.* **2004**, *69*, 475 – 481.
[27] E. Tretyakov, S. Tolstikov, A. Mareev, A. Medvedeva, G. Romanenko, D. Stass, A. Bogamyakov, V. Ovcharenko, *Eur. J. Org. Chem.* **2009**, 2548 – 2561.
[28] J. Zhang, M. Zhao, G. Cui, S. Peng, *Bioorg. Med. Chem.* **2008**, *16*, 4019 – 4028.
[29] V. Lakshmi, W.-Z. Lee, M. Ravikanth, *Dalton Trans.* **2014**, *43*, 16006 – 16014.
[30] A. Caneschi, D. Gatteschi, R. Sessoli, P. Rey, *Acc. Chem. Res.* **1989**, *22*, 392 – 398.
[31] C. Hirel, D. Luneau, J. Pecaut, L. Ohrstrom, G. Bussiere, C. Reber, *Chem. Eur. J.* **2002**, *8*, 3157 – 3161.
[32] A. T. R. Williams, S. A. Winfield, J. N. Miller, *Analyst* **1983**, *108*, 1067 – 1071.

Manuscript received: October 16, 2017
Accepted manuscript online: December 14, 2017
Version of record online: February 5, 2018

© 2018 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim