ORGANIC
LETTERS

2013
Vol. 15, No. 24
6282–6285

Inexpensive and Efficient Ullmann Methodology To Prepare Donor-Substituted Porphyrins

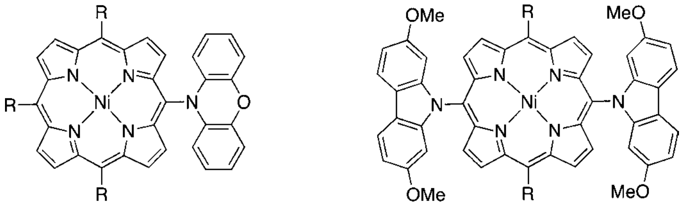
Julien Haumesser,[†] Ana M. V. M. Pereira,[†,‡] Jean-Paul Gisselbrecht,[†] Khalissa Merahi,[†] Sylvie Choua,[†] Jean Weiss,[†] José A. S. Cavaleiro,[‡] and Romain Ruppert*[,†]

Institut de Chimie, UMR 7177 du CNRS, Université de Strasbourg, 1 rue Blaise Pascal, 67000 Strasbourg, France and Department of Chemistry and QOPNA, University of Aveiro, 3810-193 Aveiro, Portugal

rruppert@unistra.fr

Received October 31, 2013

ABSTRACT



The preparation of porphyrins functionalized with one or two carbazoles (or phenoxazines) is described. The electron donors were introduced into one or two porphyrin *meso* positions by using the inexpensive Ullmann coupling procedure. Very good yields were obtained, and for two new compounds, the X-ray structures were solved. Preliminary electrochemical data coupled with electronic spectroscopy are also reported.

The use of large aromatic moieties substituted with electron donors is currently a rapidly developing area due to the potential applications of these compounds as push–pull chromophores or as sensitizers in solar cells.[1] The most efficient "Grätzel cell" described to date incorporates a porphyrin bearing an electron-donating diarylamine in one *meso* position as a light collecting subunit.[2,3]

Porphyrins bearing electron donors in the 5,15 *meso* positions were recently prepared and studied as new organic intervalent compounds with interesting electronic properties.[4] From a synthetic point of view, introducing large aromatic groups in the *meso* positions is not an easy task due to the steric hindrance of the two neighboring pyrrolic hydrogen atoms. Nevertheless, over the past few years, the teams of Anderson and Senge developed special routes to introduce anthracenyl groups in the *meso* positions.[5]

Until very recently, methods leading to the creation of a new C–N bond starting from a halogenated *meso* position yielded the desired product in moderate to good yield. In particular, the introduction of large poorly nucleophilic amines by the so-called Buchwald–Hartwig coupling was especially difficult,[6] hampering the introduction of good electron-donating groups such as carbazoles, phenoxazines,

---

[†] Université de Strasbourg.
[‡] University of Aveiro.

(1) (a) Panda, M. K.; Ladomenou, K.; Coutsolelos, A. G. *Coord. Chem. Rev.* **2012**, *256*, 2601. (b) Wang, X. F.; Tamiaki, H. *Energy Environ. Sci.* **2010**, *3*, 94.

(2) (a) Yella, A.; Lee, H. W.; Tsao, H. N.; Yi, C.; Chandiran, A. K.; Nazeeruddin, M. K.; Diau, E. W.-G.; Yeh, C. Y.; Zakeerudin, S. M.; Grätzel, M. *Science* **2011**, *334*, 629.

(3) (a) Lee, C. W.; Lu, H. P.; Lan, C.-M.; Huang, Y.-I.; Liang, Y.-R.; Yen, W.-N.; Liu, Y.-C.; Lin, Y.-S.; Diau, E. W.-G.; Yeh, C.-Y. *Chem.—Eur. J.* **2009**, *15*, 1403. (b) See also: Ishida, M.; Hwang, D.; Koo, Y. B.; Sung, J.; Kim, D. Y.; Sessler, J. L.; Kim, D. *Chem. Commun.* **2013**, *49*, 9164.

(4) (a) Sakamoto, R.; Sasaki, T.; Honda, N.; Yamamura, T. *Chem. Commun.* **2009**, 5156. (b) Sakamoto, R.; Nishikawa, M.; Yamamura, T.; Kume, S.; Nishihara, H. *Chem. Commun.* **2010**, *46*, 2028.

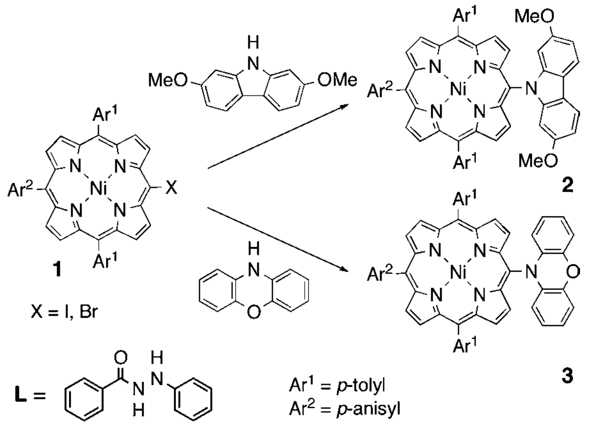
(5) (a) Davis, M.; Senge, M. O.; Locos, O. B. *Z. Naturforsch.* **2010**, *65b*, 1472. (b) Davis, N. K. S.; Pawlicki, M.; Anderson, H. L. *Org. Lett.* **2008**, *10*, 3945. (c) Davis, N. K. S.; Thompson, A. L.; Anderson, H. L. *Org. Lett.* **2010**, *12*, 2124. (d) Davis, N. K. S.; Thompson, A. L.; Anderson, H. L. *J. Am. Chem. Soc.* **2011**, *133*, 30.

(6) (a) Esdaile, L. J.; Senge, M. O.; Arnold, D. P. *Chem. Commun.* **2006**, 4192. (b) Pereira, A. M. V. M; Neves, M. G. P. M. S.; Cavaleiro, J. A. S.; Jeandon, C.; Gisselbrecht, J.-P.; Choua, S.; Ruppert, R. *Org. Lett.* **2011**, *13*, 4742. (c) Wolfe, J. P.; Wagaw, S.; Buchwald, S. L. *J. Am. Chem. Soc.* **1996**, *118*, 7215. (d) Chen, Y.; Zhang, X. P. *J. Org. Chem.* **2003**, *68*, 4432. (e) Fields, K. B.; Ruppel, J. V.; Snyder, N. L.; Zhang, X. P. In *Handbook of Porphyrin Science*; Kadish, K. M., Smith, K. M., Guilard, R., Eds.; World Scientific: Singapore, 2010; Vol. 3, p 367.

10.1021/ol403132f

or phenothiazines in the *meso* positions with good yields. Among other possible synthetic routes, the group of Imahori used gold complexes to introduce diarylamines in *meso* or β positions with moderate yields.[7] Very recently, the group of Osuka was able to introduce some of these donating groups[8a] in good yields by using the Pd−PEPPSI methodology.[8b] We previously reported that it was possible to prepare porphyrins *meso*-substituted with one or two imidazole groups by utilizing modern Ullmann coupling methodology.[9] This method represents an inexpensive and convenient alternative to the palladium- or gold-catalyzed couplings reported previously.

Scheme 1. Synthesis of Monosubstituted Nickel Porphyrins[a]



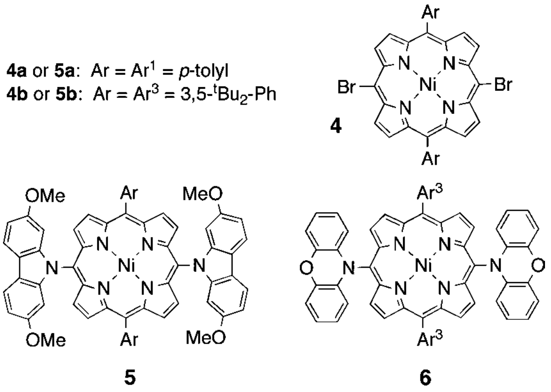
[a] Reaction conditions: porphyrin **1**, *N*-donor (10 equiv) CuI (0.1 equiv), ligand **L** (0.2 equiv), Cs_2CO_3 (2 equiv), DMSO during 12 h at 120 °C under Ar.

In this work, we describe novel applications of this reaction to introduce larger donating groups of interest, namely carbazoles or phenoxazines. The use of the *N*-phenylbenzohydrazide ligand **L** (Scheme 1) combined with copper(I) iodide was initially proposed by Li et al. in 2011.[9b] Starting from the nickel porphyrin **1** and 10 equiv of amine, the reaction in the presence of 0.1 equiv of CuI, 0.2 equiv of ligand **L**, and 2 equiv of Cs_2CO_3 in DMSO at 120 °C under argon overnight gave the desired compounds **2** or **3** in 70% or 56% isolated yield, respectively.

This coupling reaction worked in a similar way with unsubstituted carbazole (see the Supporting Information for X-ray picture), but 2,7-dimethoxycarbazole was used instead of carbazole to ensure that the oxidation potential of the aromatic amine was lower than that of the nickel porphyrin (vide infra). Furthermore, the coupling could be performed with hindered acyclic aromatic amines. The coupling reaction between 5-bromoporphyrins and 5-aminoporphyrins led to the diporphyrinylamines in a yield comparable to that observed with the Pd(II)BINAP catalytic system (48% isolated yield after 2.5 h of reaction).[6b] However, we were unable to introduce tosylamides or more encumbered cyclic amines such as iminostilbene or iminodibenzyl.

Because of their unusual electronic properties, porphyrins substituted with two electron-donating substituents are among the highly attractive organic molecules that display intervalent properties.[4,10] This prompted us to investigate the double-Ullmann coupling starting from the easily accessible 5,15-dibromonickelporphyrins **4a** or **4b** (Scheme 2).

Scheme 2. Doubly Functionalized Nickel Porphyrins[a]



[a] Reaction conditions: porphyrin **4**, *N*-donor (10 equiv) CuI (0.2 equiv), ligand **L** (0.4 equiv), Cs_2CO_3 (4 equiv), DMSO during 12 h at 120 °C under Ar.

Using reaction conditions similar to those for the previous single coupling, but in the presence of twice as much copper catalyst and cesium carbonate, good to excellent yields were obtained. Nickel porphyrin **5a** and **5b**, bearing two 2,7-dimethoxycarbazole groups in opposite *meso* positions, were, respectively, isolated in 50 and 51% yield, and nickel porphyrin **6**, bearing two phenoxazine groups, was obtained in 75% isolated yield. The differences in the yields observed were mainly due to purification difficulties in some cases. All compounds were fully characterized by

---

(7) Imahori, H.; Matsubara, Y.; Iijima, H.; Umeyama, T.; Matano, Y.; Ito, S.; Niemi, M.; Tkachenko, N. V.; Lemmetyinen, H. *J. Phys. Chem. C* **2010**, *114*, 10656.

(8) (a) Fukui, N.; Cha, W.-Y.; Lee, S.; Tokuji, S.; Kim, D.; Yorimitsu, H.; Osuka, A. *Angew. Chem., Int. Ed.* **2013**, *52*, 9728. (b) Susuki, Y.; Fukui, N.; Murakami, K.; Yorimitsu, H.; Osuka, A. DOI: 10.1002/ajoc.201300162 (c) Valente, C.; Calimsiz, S.; Hou Hoi, K.; Mallik, D.; Sayah, M.; Organ, M. G. *Angew. Chem., Int. Ed.* **2012**, *51*, 3314. (d) Nowak-Krol, A.; Gryko, D. T. *Org. Lett.* **2013**, *15*, 5618.

(9) (a) Haumesser, J.; Gisselbrecht, J.-P.; Weiss, J.; Ruppert, R. *Chem. Commun.* **2012**, *48*, 11653. (b) Li, L.; Zhu, L.; Chen, D.; Hu, X.; Wang, R. *Eur. J. Org. Chem.* **2011**, 2692.

(10) Heckmann, A.; Lambert, C. *Angew. Chem., Int. Ed.* **2012**, *51*, 326.

(11) Crystal data. Compound **5b**: $C_{76}H_{74}N_6NiO_4$, M = 1194.12 g·mol^{-1}, 0.30 × 0.15 × 0.12 mm red prisms, monoclinic, space group $C2/c$, a = 26.4946(7) Å, b = 14.0612(4) Å, c = 18.8223(5) Å, α = 90.00°, β = 109.885°, γ = 90.00°, V = 6736.7(3) Å^3, Z = 4, T = 173 K, Mo Kα = 0.71073, 1.60 < θ < 30.14, 52787 reflections measured, 9886 unique reflections, R_1 = 0.0515, wR_2 = 0.1089, GoF = 0.966. CCDC 969674 Compound **6**: $C_{76}H_{70}Cl_{12}N_6NiO_2$, M = 1583.49 g·mol^{-1}, 0.50 × 0.18 × 0.10 mm red prisms, monoclinic, space group $P2_1/c$, a = 9.5296(3) Å, b = 24.1084(7) Å, c = 18.8064(5) Å, α = 90.00°, β = 119.824°, γ = 90.00°, V = 3748.41(19) Å^3, Z = 2, T = 173 K, Mo Kα = 0.71073, 1.69 < θ < 29.99, 33553 reflections measured, 10918 unique reflections, R_1 = 0.0717, wR_2 = 0.1848, GoF = 1.045. CCDC 969675.

standard spectroscopic techniques (see the Supporting Information for detailed procedures and data), and single crystals suitable for X-ray crystallography were obtained for compounds **5b** and **6**.

Crystals of compound **5b** were obtained by slow vapor diffusion of methanol in dichloromethane, whereas compound **6** was crystallized from chloroform and methanol. Both structures are shown in Figure 1. In both structures, the relative planarity of the nickel porphyrins is quite surprising because in general nickel porphyrins are strongly ruffled.[12] The coordination geometry around the nickel(II) ion is almost square planar in the two structures. The carbazole (or phenoxazine) group is almost perpendicular to the porphyrin plane, exhibiting a dihedral angle between both planes close to 84° (or 85° respectively). The nitrogen to nitrogen distances (N atoms belonging to the donor carbazole or phenoxazine) are, respectively, 9.59 and 9.63 Å.

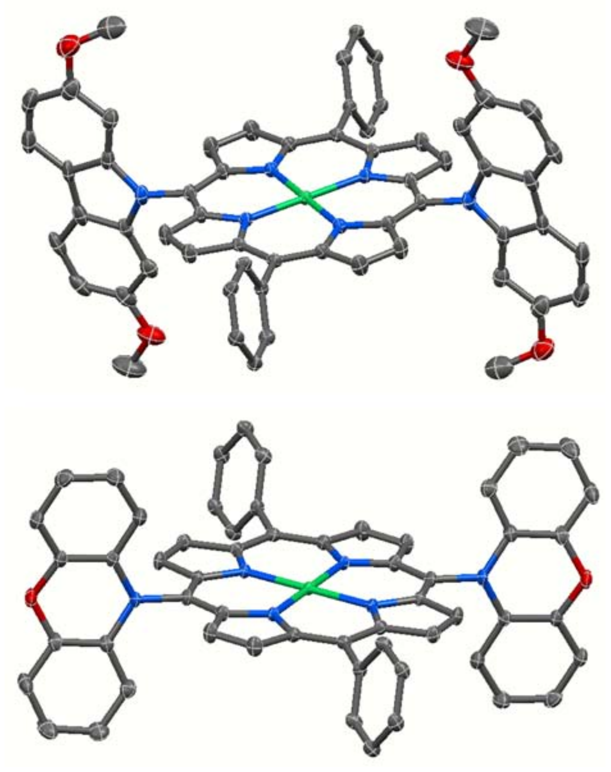


Figure 1. X-ray structure of nickelporphyrin **5b** (top) and **6** (bottom) (all hydrogen atoms and the *tert*-butyl groups were omitted for clarity).[11]

To check if the assumption that the 2,7-dimethoxycarbazole and phenoxazine groups would be oxidized before the aromatic porphyrin core, electrochemical studies were performed on the new compounds. All potentials (in volts vs Fc/Fc$^+$) are summarized in Table 1. As expected for nickel porphyrins, all compounds were reduced twice in the potential range accessible in dichloromethane. The first reduction potentials, all reversible, were found at −1.70 V for compounds **2** and **3**, whereas the first reduction potentials of compounds **5a** and **6** were less cathodic and, respectively, equal to −1.62 and −1.64 V. The second reduction occurred at potentials closer to the solvent reduction, and the electron exchange appeared to be less reversible (see Figure 2 for compounds **3** and **6**).

Table 1. Electrochemical Data for the Four New Compounds[a]

compd	reduction and oxidation potentials (volts vs Fc/Fc$^+$)			
2	−1.70 (1)	0.60 (1)	0.75 (2)	
3	−1.70 (1)	0.36 (1)	0.84 (2)	
5a	−1.62 (1)	0.65 (2)	0.85 (2)	
6	−1.64 (1)	0.37 (1)	0.43 (1)	0.99 (2)

[a] Cyclic voltammetry performed in dichloromethane containing NBu_4PF_6 (0.1 M) at a scan rate of 100 mV/s, WE: glassy carbon. In each case, the number of electrons exchanged (given in the parentheses) was determined by rotating disk voltammetry measurements (RDV).

In oxidation, for both compounds **2** and **3**, two successive waves with, respectively, one and two electrons exchanged were observed (determined by rotating disk voltammetry). In each case, three oxidation steps were expected, as two electrons can be abstracted from the nickel porphyrins and one electron from the donor (carbazole or phenoxazine). To clearly assign the oxidation sites, we recorded the EPR spectrum of the product generated after

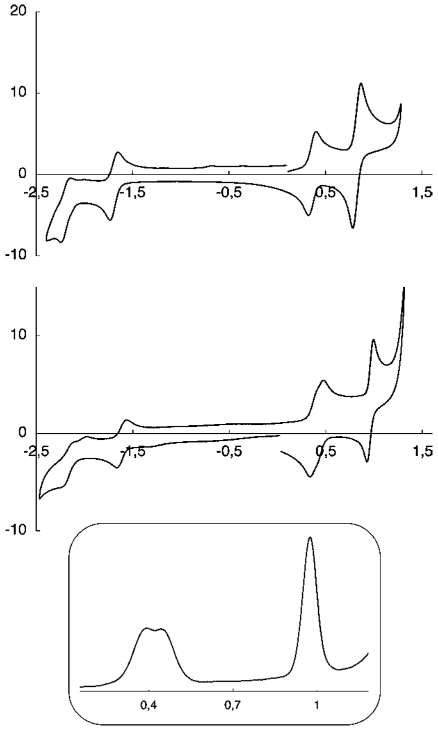


Figure 2. Cyclic voltammetry of compound **3** (top) and **6** (middle); deconvoluted oxidation curve of **6** (bottom).

---

(12) See: Senge, M. O.; Davis, M. *Acta Crystallogr.* **2010**, *E66*, m790 and references cited therein.

the first oxidation step in the case of compound **3** (see Figure 3). Compound **3** was chosen due to the significant separation between the first and the second oxidation steps. The EPR signal obtained clearly showed that the first electron was removed from the nitrogen atom of the aromatic phenoxazine donor.

Simulation of the spectrum yielded coupling constants with one ^{14}N atom equal to 8.3 G and with one set of two hydrogen atoms equal to 2.9 G. The nickel porphyrin loses then two electrons at the same potential value of 0.84 V. The electrochemistry of the mono carbazole substituted nickel porphyrin **2** can be rationalized in a similar way. The fact that the first electron is not removed from the porphyrin ring was further confirmed by the large difference between the optical gap ($\lambda_{\max} = 530$ nm or 2.33 eV for compounds **2** and **3**) and the electrochemical gap ($E_{\mathrm{ox1}} - E_{\mathrm{red1}} = 2.30$ and 2.06 V for compounds **2** and **3**, respectively).

For compounds **5a** and **6**, we expected to remove four electrons from the molecules: two from the two donors and two from the nickel porphyrins. The cyclic voltammetry of compound **6** indeed showed the removal of four electrons; the first two one-electron waves were separated by approximatively 60 mV, whereas the two other electron exchanges occurred at the same potential (see Figure 2, especially the deconvoluted curve for the oxidation part). By analogy with the behavior of compound **3**, the first electron exchanges can be attributed to the oxidation of the two phenoxazine donors (at potentials of 0.37 and 0.43 V) followed by the two electron oxidations of the porphyrin core (at a potential of 0.99 V). Oxidizing compound **6** (at a potential of 0.43 V) afforded a species showing the EPR spectrum presented in Figure 3. The presence of a quintet with a line intensity ratio of 1:2:3:2:1 corresponds to two equivalent nitrogen atoms with a hyperfine coupling constant of 4 G. This value is about half the hyperfine coupling determined for compound **3** and is attributed to the biradical with a strong spin–spin exchange coupling (2J). A similar cyclic voltammetry was recorded for the biscarbazole substituted nickel porphyrin **5a**, but all four oxidations took place around 0.65 and 0.85 V for the removal of the first two and the last two electrons.

A detailed physical chemistry study of these new compounds is currently underway. Other donors (phenothiazines for example) and other metalloporphyrins have been prepared and are also under scrutiny. Of interest are the EPR studies and the electronic properties of the different oxidized species, as well as the possible interaction of these organic radicals with a paramagnetic metal ion located in the center of the porphyrin.

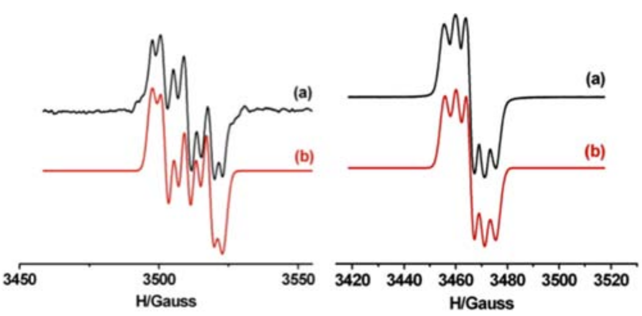


Figure 3. (Left) EPR spectrum of the electrogenerated radical cation of compound **3** in a dichloromethane solution containing NBu_4PF_6 at room temperature: (a) experimental (b) simulated. (Right) EPR spectrum of the oxidation product of compound **6** (a) experimental (b) simulated.

In conclusion, nickel porphyrins bearing one or two electron donors in the *meso* positions have been prepared in very good yield and with an extremely simple catalytic coupling system. This synthetic methodology might be useful to obtain a variety of metalloporphyrins for the design of new dyes for solar cells or new intervalent organic compounds. The presence of a metal ion inside the porphyrin core might also be of interest for the study of radical interactions in complex molecules.

Acknowledgment. We thank L. Brelot and C. Bailly from the X-ray facilities of the University of Strasbourg for solving the structures. We thank the CNRS, the Université de Strasbourg, and FCT (Portugal) for continuous financial support. We thank also FCT (fellowship to A.M. V.M.P.) and the Fondation Recherche Chimie (fellowship to K.M.).

Supporting Information Available. Experimental procedures, full characterization, and spectral data of all new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

The authors declare no competing financial interest.