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Insights into the Synthesis and the Solution Behavior of *meso*-Aryloxy- and Alkoxy-Substituted Porphyrins

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meso-RO-appended (R = alkyl, aryl) porphyrins bearing one or two OR substituents at the tetrapyrrolic macrocycle were synthesized in good yields from 5,15-dibromo-10,20-diphenylporphyrins 2H(Br_2DPP), Ni(Br_2DPP) and Zn(Br_2DPP) using an S_NAr reaction. By varying the solvent, the base, the temperature, and the time of the reaction, the optimum conditions were established, and the selective introduction of one or two *meso*-RO substituents at the periphery of the macrocycle was achieved. Moreover, monofunctionalization of Ni(Br_2DPP) according to an S_NAr reaction was used as a key step for the synthesis of rarely explored unsymmetrical porphyrinyl alkyl ethers. ^{1}H NMR studies of these ethers in $CDCl_3$ revealed concentration-dependent aggregation of the zinc derivative through coordination of the central metal ion of one molecule to the peripheral oxygen atom of a second tetrapyrrolic macrocycle.

Introduction

Tetrapyrrolic ligands are widely used in Nature and, in the last century, there has been impressive developments in this field, with porphyrin complexes now being considered as potential candidates for practical use in solar energy transformations, medicinal chemistry, photocatalysis and so forth.[1–8] To answer increasing demands of physicists, biologists, and engineers, efficient synthetic approaches for the functionalization of the macrocyclic periphery of porphyrins is required because it was recognized that this is one of the simplest and most efficient ways to modulate the properties of metalloporphyrinates and to elaborate multiporphyrinic arrays or supramolecular assemblies. Considerable efforts have therefore been devoted to the synthesis of such structures and these have revealed the key role of post-functionalization strategies for the preparation of porphyrins.[9–12] This approach relies on the rich and unique chemistry of tetrapyrrolic macrocycles, which can be easily transformed into useful synthons such as halo-, nitro- and formyl-substituted derivatives. Depending on the structural parameters of the porphyrins, both electrophilic and nucleophilic aromatic substitution reactions can be applied for the synthesis of target molecules.[10] However, nucleophilic aromatic substitution (S_NAr) reactions usually require drastic conditions to proceed.[13–21] Therefore, transition-metal-catalyzed reactions were developed as an alternative route to carry out the reactions of haloporphyrins with nucleophiles[11,12,22–28] but these reactions also suffer serious drawbacks such as a limited substrate tolerance, the need for specific and expensive ligands, high catalyst loading and time-consuming optimization of experimental conditions; furthermore, difficulties are encountered in reproduction and upscale experiments, and because of contamination of products by toxic metals. For these reasons, it is perhaps not surprising that S_NAr reactions as a tool for the preparation of *C*-, *O*-, *S*- and *N*-substituted porphyrins have recently been revisited.[1–8,29–33] However, most of these S_NAr reactions involve Ni^{II} porphyrinates or amines as nucleophiles. It is well known that Ni^{II} porphyrinates afford functionalized compounds that do not tolerate the drastic conditions of a demetallation reaction and, consequently, are not very useful for the preparation of various porphyrin complexes that are needed for the myriad practical applications. Thus, S_NAr reactions still require further development before they can be used for efficient functionalization of porphyrins.

In parallel with other groups,[9–12,29,32,34] in this work, we have investigated the use of catalyst-free C–O bond-forming reactions to prepare rarely studied but useful[10,28,35] *meso*-RO-substituted (R = alkyl, aryl) porphyrins. To expand the scope of the nucleophilic substitution reaction for the synthesis of porphyrins, we studied the reaction of

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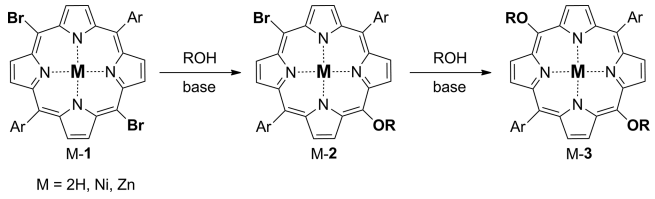
2H(Br_2DPP), Zn(Br_2DPP) and Ni(Br_2DPP) (M-**1**, M = 2H, Zn and Ni), which are readily available[36,37] and can afford mono- or di-OR-substituted porphyrins M-**2** and M-**3** upon reaction with alcohols (Scheme 1).



Scheme 1. S_NAr reactions of M(Br_2DPP).

However, achieving selectivity is challenging for both transformations. Indeed, the first selective substitution of the bromine atom leading to M-**2** is limited because of the drastic conditions required for the reaction. Furthermore, the second substitution reaction, affording M-**3**, is hindered by the strong electron-donating alkoxy substituent. To our knowledge, only one example of the catalyst-free double nucleophilic substitution is described for 5,15-dibromoporphyrins, namely the reaction of Zn-**1** (Ar = 3,5-di-*t*Bu-C_6H_3) with morpholine.[20,21] In the context of our project on metal-organic materials, we were interested in porphyrins decorated by aryloxy and long-chain alkoxy groups. The primary alcohols react with difficulty with aromatic halides according to transition-metal-catalyzed reactions, and sophisticated ligands are needed to obtain these compounds in moderate to good yields.[11,12,22–28] Therefore, the development of catalyst-free conditions were of particular interest for these reactions.

Here, we report the optimum conditions that were developed to obtain mono- and di-OR-substituted porphyrins from 5,15-dibromoporphyrins M-**1**. Moreover, we demonstrate that mono-substituted derivatives M-**2**, bearing a bromine substituent, are convenient precursors for Pd-catalyzed cross-coupling reactions leading to a series of little-studied porphyrinyl alkyl ethers. Our preliminary studies on the solution aggregation of ethers M-**2** by using ^{1}H NMR spectroscopy, are also described. These data indicate that porphyrinyl alkyl ethers form supramolecular assemblies resulting from axial binding of the oxygen atom of the alkoxy group from one porphyrin molecule to the metal center of a second molecule. This coordination-driven self-assembly is of interest for crystal engineering and material chemistry.

Results and Discussion

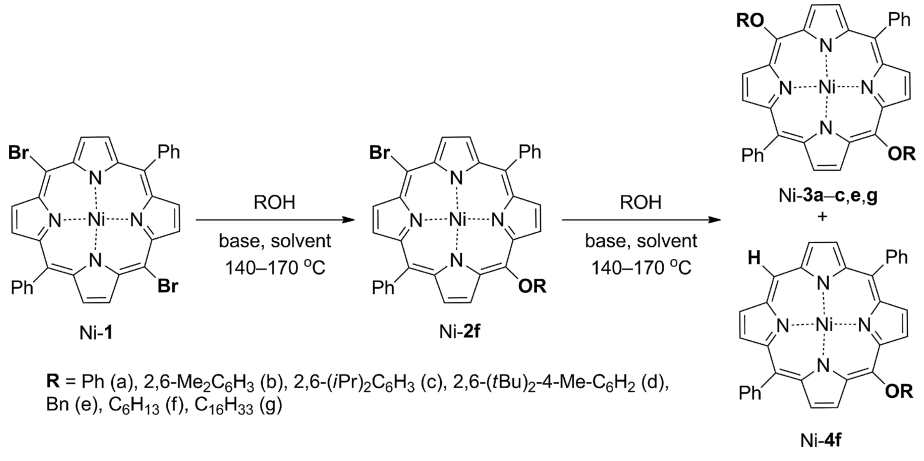
To access the potential of the S_NAr reaction for 5,15-dibromoporphyrins M-**1**, we first investigated the reaction of Ni^{II} complex Ni-**1** with phenols and primary alcohols (Scheme 2); the results are summarized in Table 1.

Table 1. S_NAr reaction of Ni-**1** with O-nucleophiles.[a]

	ROH [equiv.]	Solvent	*T* [°C]	*t* [h]	Yield [%][b] Ni-**1**	Ni-**2**	Ni-**3**
1	PhOH (15)	DMA	120	1	0	0	72
2	2,6-$Me_2C_6H_3OH$ (15)	DMA	120	1	0	0	77
3	2,6-*i*$Pr_2C_6H_3OH$ (15)	DMA	120	6	0	0	17[c]
4	2,6-*t*Bu_2-4-Me-C_6H_2OH (15)	DMA	120	6	0	0	0
5	BnOH (80)	DMA	120	6	0	0	62
6	HexOH (66)	DMA	120	6	0	42	0
7	HexOH (66)	DMA	120	3	13	50	0
8	HexOH (66)	diglyme	120	3	33[d]	66[d]	0
9	HexOH (66)	diglyme	170	1	36[d]	46[d,e]	0
10	HexOH (66)	diglyme	145	6	6	57	0

[a] Reaction conditions: suspension of Ni-**1** (50 mg, 0.074 mmol), an excess of alcohol and Cs_2CO_3 (72 mg, 3 equiv.), solvent (9.4 mL), heated under Ar. [b] Isolated yield. [c] Isolated as a mixture with 2,6-*i*$Pr_2C_6H_3OH$ (1:1). The yield was determined by NMR spectroscopic analysis. [d] Determined by MALDI-TOF MS analysis. [e] Ni-**4f** (18%) was also observed by MALDI-TOF MS analysis.

The catalyst-free nucleophilic substitution of a bromine atom by phenol was described for activated aromatic compounds[38] and for nickel(II) 5-bromoporphyrinates while our work was in progress.[29] Ni-**1** also reacted smoothly with an excess (15 equiv.) of phenol in the presence of Cs_2CO_3 (3 equiv.) in DMA at 120 °C and afforded di-OR-substituted porphyrin Ni-**3a** in 72% yield (100% conversion) after 1 h (Table 1, entry 1). Under these conditions,



Scheme 2. S_NAr reactions of Ni-**1** with phenols and primary alcohols.

2,6-dimethylphenol gave diether Ni-**3b** in 77% yield (entry 2). However, the same reaction using more sterically hindered phenols was inhibited. 2,6-Diisopropylphenol afforded Ni-**3c** in only 17% yield after 6 h [20% conversion according to MALDI-TOF mass spectrometry (MS)] (entry 3) and no reaction occurred with 2,6-di-*tert*-butyl-4-methylphenol (entry 4). It should be noted that monosubstituted products Ni-**2a**–**d** were never observed in these reactions.

The reaction of Ni-**1** with benzyl alcohol under analogous reaction conditions also gave only diether Ni-**3e** after 6 h (entry 5). Despite full consumption of the starting porphyrin, Ni-**3e** was isolated in only 62% yield because the compound was unstable under the reaction conditions.

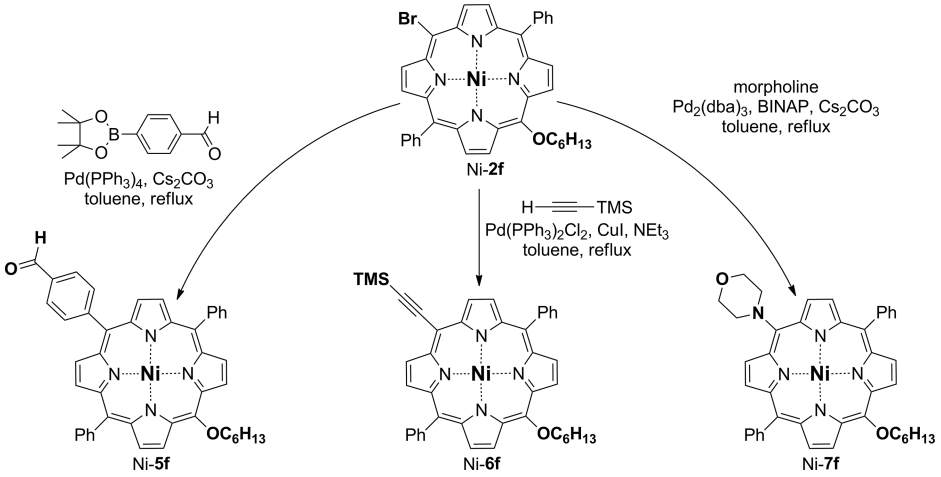
The reaction of Ni-**1** with less acidic 1-hexanol and Cs_2CO_3 (3 equiv.) in DMA proceeded more slowly than with phenols. For example, when Ni-**1** was treated with 1-hexanol (66 equiv.), complete conversion was reached after 6 h and a selective substitution of one bromine atom was observed according to MALDI-TOF MS (entry 6). Selective substitution of a bromine atom by O-nucleophiles in 5,15-dibromoporphyrins is unusual but it was previously observed in the reaction of nickel(II) 5,15-dibromoporphyrinates with phenols in the presence of Ni-catalysts.[27] Despite full conversion of Ni-**1**, ether Ni-**2f** was isolated in only 42% yield, indicating concomitant degradation of the porphyrin macrocycle under the reaction conditions. A slightly higher yield of Ni-**2f** (50%) with 87% conversion of Ni-**1** was obtained when heating was stopped after 3 h (entry 7). Our attempts to optimize the product yield by using different solvents (*N*,*N*-dimethylformamide (DMF), *o*-dichlorobenzene, nitrobenzene, diglyme) and varying the temperature gave only moderate success. The best results were obtained in diglyme after careful optimization of the reaction temperature. In this solvent, at 120 °C, the reaction was slower than in DMA (entries 7 and 8). When the temperature was increased to 170 °C the selectivity was lost and a mixture of Ni-**2f** and Ni-**4f** was obtained even after 1 h, when complete conversion of Ni-**1** was not yet reached (entry 9). It seems that, under these reaction conditions, 1-hexanol also serves as a reducing agent, as in the case of early reported reductions of aryl halides with alcohols in the presence of transition-metal catalysts[39–41] and under catalyst-free conditions.[39] When Ni-**1** was treated with 1-hexanol at 145 °C, the side reaction was suppressed, and preparative chromatography of the reaction mixture gave Ni-**2f** in 57% yield (entry 10).

Ni-**2f** can be used as a convenient precursor for various nonsymmetrical *meso*-alkoxyporphyrins due to the presence of reactive bromine in this molecule.[10] In this work, we investigated Pd-catalyzed cross-coupling reactions, which are summarized in Scheme 3.

Coupling of Ni-**2f** with (4-formylphenyl)pinacolborane or (trimethylsilyl)acetylene, according to Suzuki–Myaura or Sonogashira reactions, afforded Ni-**5f** and Ni-**6f** in 62 and 63% yield, respectively. Pd-catalyzed C–N bond-forming reactions seem to be more difficult because of the strong electron-donating character of the alkoxy substituent. However, the reaction with morpholine proceeded even in the presence of a typical Pd_2dba_3-BINAP precatalyst and Cs_2CO_3, affording Ni-**7f** in 25% yield.

These examples demonstrate that S_NAr reactions of Ni(Br_2DPP) are of interest for the preparation of porphyrinyl ethers, including unsymmetrical derivatives, which have attracted significant attention in the field of porphyrin science.[10,42] However, their application as a tool for porphyrin synthesis is limited by the drastic conditions required for demetallation that needs to be performed prior to the preparation of various complexes. Indeed, the demetallation of Ni^{II} porphyrinates is only observed in the presence of strong acids[43] and our numerous attempts to obtain free-base porphyrins from Ni-**2f** and Ni-**3a**–**c** without degradation of the porphyrin macrocycle were unsuccessful. For example, no demetallation reaction occurred when Ni-**2f** was treated with trifluoroacetic acid (TFA) in chloroform, but the reaction with H_2SO_4 in CH_2Cl_2 led to the hydrodebromination of Ni-**2f** and afforded Ni-**4f** according to MALDI-TOF MS analysis.

Consequently, to obtain metal complexes of *meso*-alkoxyporphyrins, the reactions of Zn^{II} complexes



Scheme 3. Pd-catalyzed cross-coupling reactions of Ni-**2f**.

Zn(Br_2DPP) (Zn-**1**) and free-base 2H(Br_2DPP) (2H-**1**) with alcohols were studied (see Tables 2 and 3, Schemes 4 and 5). A significant difference in the reactivity of these compounds and Ni(Br_2DPP) was observed when these compounds were treated with 1-hexanol, which was taken as a model alcohol.

Table 2. S_NAr reaction of Zn-**1** with 1-hexanol.[a]

	Base [equiv.]	Solvent	*T* [°C]	*t* [h]	Yield [%][b] Zn-**1**	Zn-**2f**	Zn-**3f**	Zn-**4f**	Zn-**8**
1	Cs_2CO_3 (3)	diglyme	145	6	0	26	0	10	0
2	Cs_2CO_3 (3)	diglyme	170	1.5	0	50[c]	0	50[c]	0
3	Cs_2CO_3 (1)	diglyme	170	3.5	0	56[c]		0	44[c]
4[d]	Cs_2CO_3 (3)	DMA	120	6	0	48[e]	0	19[e]	0
5	Cs_2CO_3 (3)	DMA	100	15	40[e]	49[e]	0	0	0
6[d]	HexOLi (100)	HexOH	170	1	0	0	24	42	28
7	HexOLi (10)	HexOH	170	3	0	0	8	57	17

[a] Reaction conditions: Zn-**1** (20 mg, 0.03 mmol), 1-hexanol (0.25 mL, 66 equiv.), base, solvent (3.75 mL), heated under Ar. [b] Determined by ^1H NMR spectroscopic analysis. [c] Determined by MALDI-TOF MS analysis. [d] Upscale to 50 mg (0.074 mmol) of Zn-**1**. [e] Isolated yield.

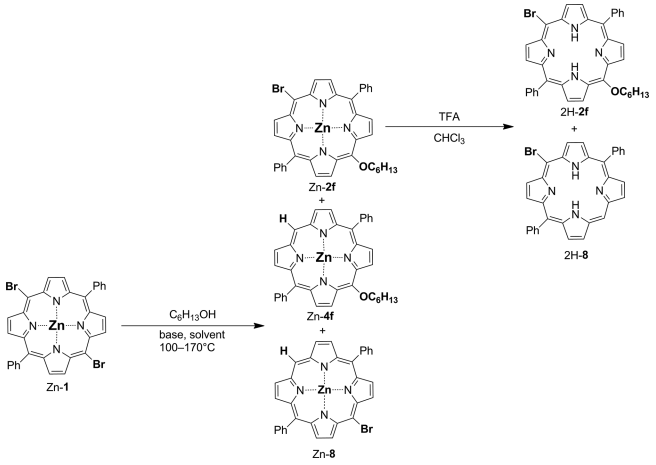
Zn-**1** reacted with 1-hexanol at higher temperature compared with Ni-**1**, affording the desired product in low yields because of a competing hydrodebromination reaction and considerable degradation of the porphyrins (Scheme 4 and Table 2).

The structure of the side products and their amount was dependent on the reaction temperature, the nature of the base and the solvent, as well as on the amount of base that was introduced into the reaction. Under the optimal conditions used for the preparation of Ni-**2f** (Cs_2CO_3, diglyme, 145 °C), the reaction of Zn-**1** afforded an inseparable mixture of Zn-**2f** and Zn-**4f** (2:1 ratio) in 36% yield (Table 2, entry 1).

Table 3. S_NAr reaction of 2H-**1** with 1-hexanol.[a]

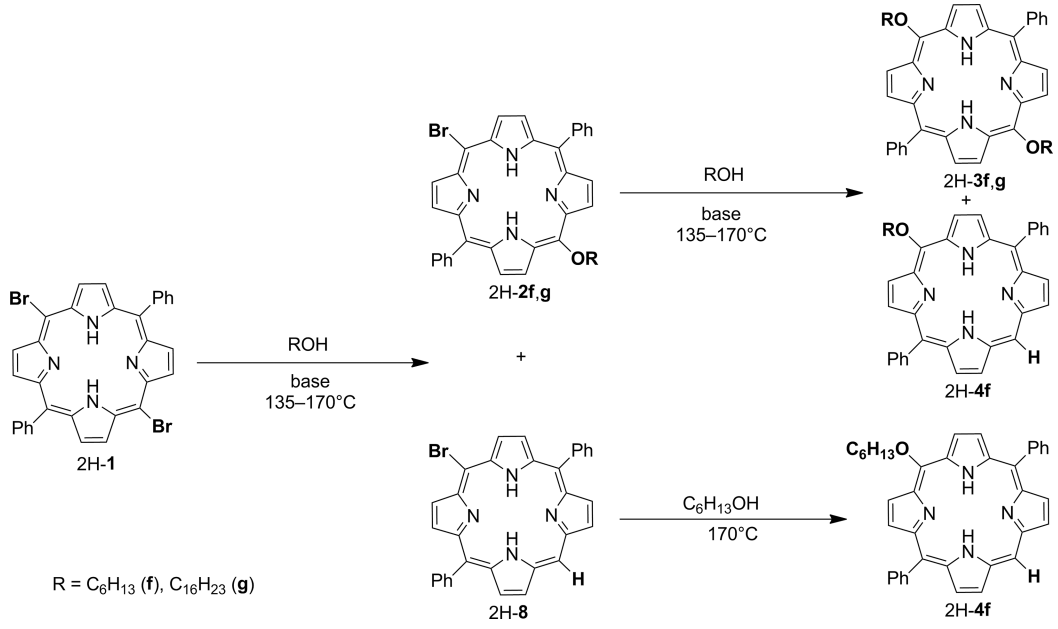
Entry	Base [equiv.]	*T* [°C]	*t* [h]	Yield [%][b] 2H-**1**	2H-**2f**	2H-**3f**	2H-**4f**
1	Cs_2CO_3 (1)	145	7	50	50	0	0
2	Cs_2CO_3 (1)	170	24	0	0	16	84
3	Na_2CO_3 (3)	170	24	0	100 (64)	0	0
4[c]	Cs_2CO_3 (3)	170	1	0	0	90 (86)	10 (9)
5[d]	Na_2CO_3 (30)	170	24	0	0	0	0
6	Na_2CO_3 (30)	135	24	100	0	0	0

[a] Reaction conditions: 2H-**1** (20 mg, 0.03 mmol), the base heated in 1-hexanol (4 mL) under Ar. [b] Determined by MALDI-TOF MS analysis. Isolated yields are given in parentheses. [c] Upscale to 50 mg (0.81 mmol) of 2H-**1**. [d] Complete decomposition of the starting material.



Scheme 4. Synthesis of Zn-**2f** and 2H-**2f** using S_NAr reaction of Zn-**1** with 1-hexanol.

Upon increase of the temperature to 170 °C, the hydrodebromination reaction was favored (entry 2). Hydrodebromination was also observed when the amount of



Scheme 5. S_NAr reaction of 2H-**1** and 2H-**8** with alcohols.

Cs_2CO_3 was decreased, indicating the importance of alcohol deprotonation for successful S_NAr reaction. For example, when Cs_2CO_3 (1 equiv.) was used in diglyme at 170 °C, the side hydrodebromination of Zn-**1** gave zinc(II) 5-bromo-10,20-diphenylporphyrinate (Zn-**8**), which did not react with 1-hexanol under these conditions (entry 3). Higher selectivity of the S_NAr reaction was achieved when diglyme was replaced by DMA and the reaction was carried out at lower temperature. In this solvent, a mixture of Zn-**2f** and Zn-**4f** was still formed at 120 °C (entry 4) but a selective substitution reaction was observed at 100 °C, affording the target compound Zn-**2f** after 15 h in 49% yield with 40% recovery of the starting porphyrin (entry 5). Our attempts to replace both bromine atoms by using a stronger nucleophile such as lithium hexanolate in hexanol at 170 °C gave the target product Zn-**3f** in low yields, along with the products of the hydrodebromination reaction (entries 6 and 7).

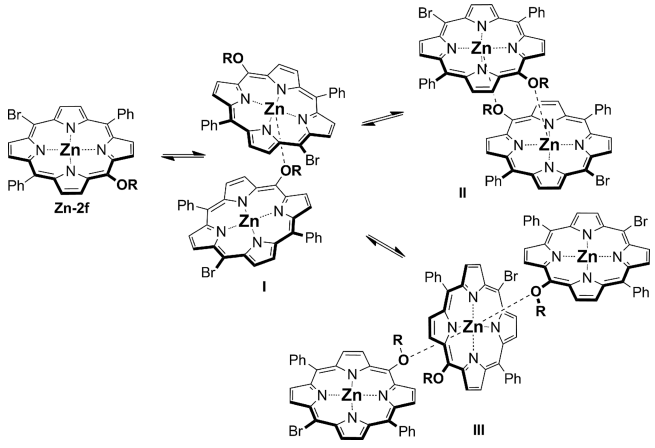
Surprisingly, the demetallation of Zn-**2f** with TFA in chloroform gave a mixture of the target compound 2H-**2f** and 5-bromo-10,20-diphenylporphyrin (2H-**8**) in a 9:1 ratio (Scheme 4). The separation of products by column chromatography was difficult and the structure of the side product was determined by comparison of the ^{1}H NMR spectroscopic data of this mixture with those of an authentic sample of 2H-**8**, and was confirmed by MALDI-TOF MS analysis. Thus, to obtain free-base porphyrin derivatives, S_NAr reaction of 2H-**1** with 1-hexanol was studied (Scheme 5).

Once again, the hydrodebromination reaction was observed and a careful optimization was needed to prepare the target products in good yields (Table 3). When the reaction was carried out using Cs_2CO_3 (1 equiv.) in 1-hexanol, selective mono-substitution was observed but the reaction proceeded slowly and only approximately 50% conversion was obtained even after 7 h (entry 1). Prolonged heating led to an increase in the amount of hydrodebromination product (entry 2). Higher yields of the target 2H-**2f** were obtained by using a weaker base, sodium carbonate, taken in excess. The reaction with Na_2CO_3 (3 equiv.) gave porphyrin 2H-**2f** in 64% yield, which was only hindered by the competing degradation reaction (entry 3). Interestingly, selective dietherification reaction was observed when sodium carbonate was replaced by Cs_2CO_3 and the target porphyrin 2H-**3f** was isolated in 86%. In contrast, an increase in the amount of sodium carbonate was inappropriate for the synthesis of diether 2H-**3f** (entries 4 and 5).

The higher homologues of 1-hexanol also reacted with 2H-**1** under the catalyst-free conditions described above. For example, the reaction of 2H-**1** with 1-hexadecanol and Cs_2CO_3 (3 equiv.) at 170 °C afforded a mixture of 2H-**3g** and 2H-**2g** in 11:1 molar ratio in 88% yield. However, separation of these compounds was challenging, and metallation with $Zn(OAc)_2$ was needed to obtain pure Zn-**3g**.

Thus, careful optimization of catalyst-free reactions of 2H-**1** with primary alcohols allowed the selective mono- and dietherification of the porphyrin macrocycle to be achieved. It is also of interest that these conditions can be used for functionalization of other *meso*-bromoporphyrins. For example, when 5-bromo-10,20-diphenylporphyrin (2H-**8**) was treated with 1-hexanol in the presence of Cs_2CO_3 (3 equiv.) at 170 °C, ether 2H-**4f** was obtained in 52% yield (Scheme 5).

Free-base porphyrinyl alkyl ethers and their complexes have seldom been studied but they are of interest for investigation of the structural and electronic influence of individual substituents on the properties of tetrapyrrolic macrocycles. In a continuation of our project aimed at the study of porphyrin assemblies formed through weak coordination bonds,[44–48] we investigated the solution behavior of ether Zn-**2f**. Aromatic ethers easily form complexes with transition-metal ions and we expected to observe a coordination-driven self-assembly of alkoxy-substituted metalloporphyrinates due to the axial coordination of the oxygen atom of the alkoxy group to the central metal cation of a second porphyrin macrocycle, as shown in Scheme 6.



Scheme 6. Schematic representation of Zn-**2f** self-assemblies.

To gain initial insight into the self-assembly of porphyrinyl alkyl ethers, ^{1}H NMR spectra of Zn-**2f** were recorded at a range of concentrations in $CDCl_3$ and compared with those of Ni-**2f**, which is not able to form supramolecular complexes under the experimental conditions studied (Figure 1A and B). As expected, negligible changes in the spectrum of Ni-**2f** were observed when the concentration of the complex was increased from 10^{-4} to 10^{-2} M (Figure 1B). In contrast, for complex Zn-**2f**, a set of sharp signals was observed at 10^{-4} M, which gradually broadened and shifted upfield upon increase of the concentration up to 6×10^{-3} M (Figure 1A). Further increase of the concentration to 10^{-2} M led to a gradual upshift of narrowing proton resonances. The concentration-induced shift was different for each of the β-protons, which were unambiguously assigned by using COSY and through-space NOE between H^2-H^3 and H^1-CH_2O protons (Figures S38–S40). These shifts decreased along the sequence H1 > H2 ≈ H3 ≈ H4, and only signals of H1 protons significantly shifted at higher concentrations of the complex (Figure 1C). It is important to note that the signals corresponding to *meso*-aryl substituents were almost identical in all spectra.

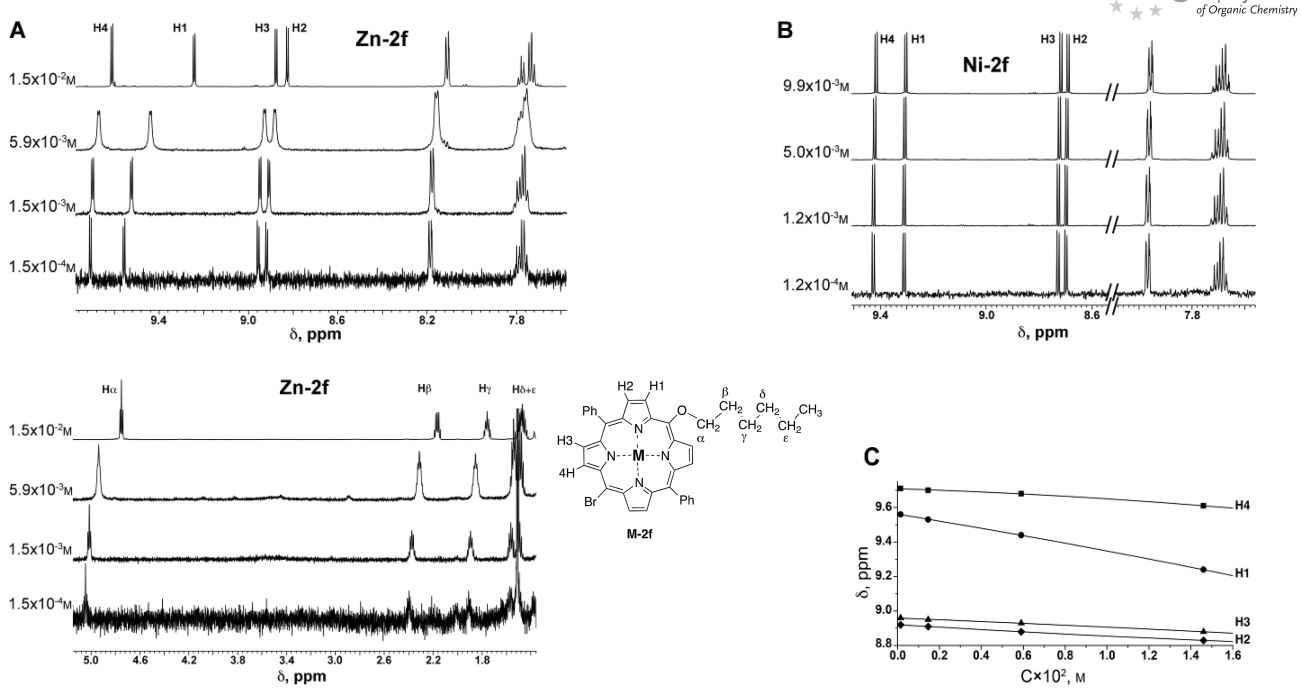


Figure 1. Partial ^{1}H NMR spectra of Zn-**2f** (A) and Ni-**2f** (B) in $CDCl_3$. Concentration dependence of the chemical shifts of the β-pyrrol protons of Zn-**2f** (C).

The spectral difference observed for Zn-**2f** and Ni-**2f** can be explained by considering that Zn-**2f** can form supramolecular assemblies, as shown in Scheme 6. Moreover, these data indicate that co-facial dimer **II** is not a major species present in the studied solutions of Zn-**2f**, because a strong upfield shift of resonances of β-pyrrol and *meso*-aryl substituent protons should be observed for dimer **II** due to ring current effects of the tetrapyrrolic macrocycles.[24,45]

The above conclusion is also supported by a comparison of structural parameters obtained for Zn-**2f** using DFT calculations with those of zinc(II) complexes bearing coordinated anisol fragment and deposited at the Cambridge Crystallographic Data Centre. Indeed, according to the geometry optimization of dimer **II** performed with the application of SPARTAN'14 software at the B3LYP/6-31G* level, the distance between macrocycles should be approximately 3.16 Å. This value is in the range of typical π–π stacking interaction values (3.4–3.6 Å).[49] However, an average Zn···O distance for zinc(II) complexes with ligands bearing an anisol fragment is much smaller (2.37 ± 0.11 Å). Accordingly, the co-facial arrangement of porphyrin macrocycles should prohibit efficient binding of the donor oxygen atom by the metal ion of another porphyrin molecule.

It is difficult to determine whether only dimer **I** or oligomers **III** are observed in 6×10^{-3} M solution of Zn-**2f** in $CDCl_3$. However, taking into account that supramolecular assemblies were detected only at the millimolar concentration of the complex, it appears that the association constant is low and that dimer **I** is a predominant species in the studied solutions. Unfortunately, our attempts to grow single crystals of Zn-**2f** were unsuccessful.

Conclusions

A series of RO-appended porphyrins was synthesized in good yields from 5,15-dibromoporphyrins M(Br_2DPP) by using S_NAr reactions. Although this reaction often proceeds in parallel with various side processes, the selectivity can be increased by varying the nature of the base and its amount, the solvent, the temperature, and the reaction time. Moreover, the S_NAr reaction can be directed to the synthesis of *meso*-substituted porphyrin decorated by one or two RO groups. This reaction is a convenient alternative to transition-metal-catalyzed C–O bond-forming reactions. Although S_NAr reactions of 5,15-dibromoporphyrins M-**1** with alcohols demand time-consuming optimization, they are less expensive, free of toxic metals, and gave, in some cases, better yields and higher selectivity than transition-metal-catalyzed coupling reactions. Monofunctionalization of 5,15-dibromoporphyrins M-**1** through S_NAr reaction is a useful tool for the preparation of porphyrinyl ethers, which have seldom been explored but which are potentially interesting derivatives, since the conjugation of the oxygen atom should induce new electronic properties. Besides being suitable starting materials for new representatives of porphyrinyl alkyl and porphyrinyl aryl series, these compounds are of interest in their own right. They allow an investigation of the structural and electronic influence of individual substituents on the tetrapyrrole macrocycle properties and are useful building blocks for crystal engineering. Our preliminary studies of the solution behavior of Zn-**2f** in chlorinated solvents testify to their ability to form supramolecular assemblies. We expect that these compounds will be

also of interest for the preparation of push–pull porphyrins and organized thin-film materials.

Experimental Section

General: Unless otherwise noted, all chemicals and starting materials were obtained from Acros or Aldrich, and were used without further purification. The starting porphyrins 2H-**1**,[36] Zn-**1**,[36] Ni-**1**[37] and 2H-**8**[37,50,51] were prepared according to published procedures. Phenol (Sigma–Aldrich, 99%), 2,6-dimethylphenol (Aldrich, 99%), 2,6-diisopropylphenol (Aldrich, 97%), 2,6-di-*tert*-butyl-4-methylphenol (Aldrich, 99%), benzyl alcohol (Aldrich, 99%), and DMA (Aldrich, 99.5%) were used as obtained. 1-Hexyl alcohol (Aldrich, 98%) was distilled from sodium and stored under argon. Diglyme (Aldrich, 99%) was distilled from NaOH and stored under argon. Chloroform and hexane (reagent grade) were dried with anhydrous $CaCl_2$ and distilled from CaH_2.

All reactions were performed in oven-dried glassware under a slight positive pressure of argon. Analytical thin-layer chromatography (TLC) was carried out with Merck silica gel 60 plates (precoated sheets, 0.2 mm thick, with fluorescence indicator F254), preparative thin-layer chromatography (PLC) was carried out with Merck silica gel 60 (precoated glass plates, 2 mm thick). Column chromatography purification was carried out with silica gel (Silica 60, 60–200 μm, Macherey–Nagel) and neutral alumina (50–200 μm, Macherey–Nagel).

NMR spectra were acquired with a Bruker Avance III 600.13 MHz and a Bruker Avance II 300.21 MHz and referenced to residual solvent protons. The unambiguous assignment of signals in the ^{1}H NMR spectra was performed by using gradient-enhanced COSY and NOESY correlation experiments. UV/Vis spectra were obtained with a Unicam UV-4 spectrophotometer in $CHCl_3$ in rectangular quartz cells with 1 cm optical path. MALDI-TOF mass-spectra were obtained with a Bruker Ultraflex mass-spectrometer in positive ion mode without application of matrix, otherwise another conditions are stated. Accurate mass measurements (HRMS) were made at the "Pôle Chimie Moléculaire", the technological platform for chemical analysis and molecular synthesis (http://www.wpcm.fr) which relies on the Institute of Molecular Chemistry of the University of Burgundy and Welience™, a Burgundy University private subsidiary. Solutions in $CHCl_3$/methanol (1:1) were used for analysis.

S_NAr Reactions of Ni(Br_2DPP) and Zn(Br_2DPP) with Phenols and Alcohols

Nickel(II) OR-Substituted Porphyrins. General Procedure: A 25 mL flask containing Ni-**1** (50 mg, 0.074 mmol) and Cs_2CO_3 (72 mg, 0.222 mmol) was evacuated and backfilled with argon three times. The solvent (9.4 mL) and the indicated amount of phenol or alcohol (Table 1) were added and the mixture was heated under argon for the time indicated (Table 1). The reaction mixture was then diluted with $CHCl_3$ (50 mL) and washed with H_2O (50 mL). The organic layer was separated, dried with Na_2SO_4, and evaporated under reduced pressure at 60 °C. The residue was purified by chromatography on silica gel ($CHCl_3$/hexane, 0→100%). The product was purified by preparative TLC (hexane/acetone, 4:1).

[5,15-Diphenoxy-10,20-diphenylporphyrinato]nickel(II) (Ni-3a): (Table 1, entry 1): Prepared by following the general procedure from Ni-**1** and phenol (104 mg, 1.11 mmol, 15 equiv.) in DMA, yield 72%; red solid. ^{1}H NMR (600 MHz, $CDCl_3$, 25 °C): δ = 9.16 (d, $^3J_{H,H}$ = 5.0 Hz, 4 H, H_β), 8.69 (d, $^3J_{H,H}$ = 4.9 Hz, 4 H, H_β), 7.97 (dd, $^3J_{H,H}$ = 8.0, $^4J_{H,H}$ = 1.4 Hz, 4 H, *o*-Ph), 7.69–7.63 (m, 6 H, *m*+*p*-Ph), 7.19 (dd, $^3J_{H,H}$ = 8.6, $^3J_{H,H}$ = 7.6 Hz, 4 H, *m*-PhO), 6.96 (t, $^3J_{H,H}$ = 7.4 Hz, 2 H, *p*-PhO), 6.86 (d, $^3J_{H,H}$ = 8.2 Hz, 4 H, *o*-PhO) ppm. UV/Vis ($CHCl_3$): λ = 417, 529, 560 (sh) nm. HRMS (ESI): *m*/*z* calcd. for $C_{44}H_{28}N_4NiO_2$ $[M]^+$ 702.15603; found 702.15817.

[5,15-Bis(2,6-dimethylphenoxy)-10,20-diphenylporphyrinato]nickel-(II) (Ni-3b): (Table 1, entry 2): Prepared by following the general procedure from Ni-**1** and 2,6-dimethylphenol (135 mg, 1.11 mmol, 15 equiv.) in DMA, yield 77%; red solid. ^{1}H NMR (300 MHz, $CDCl_3$, 25 °C): δ = 8.96 (d, $^3J_{H,H}$ = 5.0 Hz, 4 H, H_β), 8.52 (d, $^3J_{H,H}$ = 5.0 Hz, 4 H, H_β), 7.91–7.86 (m, 4 H, *o*-Ph), 7.64–7.56 (m, 6 H, *m*+*p*-Ph), 7.09–7.03 (m, 6 H, OAr), 1.98 (s, 12 H, Me) ppm. UV/Vis ($CHCl_3$): λ = 424, 544, 589 nm. MS (MALDI-TOF): *m*/*z* calcd. for $C_{48}H_{36}N_4NiO_2$ $[M]^+$ 758.22; found 758.64.

[5,15-Bis(2,6-diisopropylphenoxy)-10,20-diphenylporphyrinato]-nickel(II) (Ni-3c): (Table 1, entry 3): Prepared by following the general procedure from Ni-**1** and 2,6-diisopropylphenol (197 mg, 205 μL, 1.11 mmol, 15 equiv.) in DMA, yield 17%; red solid. ^{1}H NMR (300 MHz, $CDCl_3$, 25 °C): δ = 8.81 (d, $^3J_{H,H}$ = 5.1 Hz, 4 H, H_β), 8.47 (d, $^3J_{H,H}$ = 5.1 Hz, 4 H, H_β), 7.93–7.83 (m, 4 H, *o*-Ph), 7.68–7.54 (m, 6 H, *m*+*p*-Ph), 7.31 (br. s, 6 H, OAr), 3.20 (sept, $^3J_{H,H}$ = 6.9 Hz, 4 H, CH), 0.99 (d, $^3J_{H,H}$ = 6.9 Hz, 24 H, Me) ppm. UV/Vis ($CHCl_3$): λ = 418, 542, 572 (sh) nm. MS (MALDI-TOF): *m*/*z* calcd. for $C_{56}H_{52}N_4NiO_2$ $[M]^+$ 870.34; found 870.54. HRMS (ESI): *m*/*z* calcd. for $C_{56}H_{52}N_4NiO_2$ $[M]^+$ 870.34491; found 870.34383.

[5,15-Bis(benzyloxy)-10,20-diphenylporphyrinato]nickel(II) (Ni-3e): (Table 1, entry 5): Prepared by following the general procedure from Ni-**1** and benzyl alcohol (640 mg, 610 μL, 5.92 mmol, 80 equiv.) in DMA, yield 62%; red solid. ^{1}H NMR (600 MHz, $CDCl_3$, 25 °C): δ = 9.29 (d, $^3J_{H,H}$ = 4.8 Hz, 4 H, H_β), 8.71 (d, $^3J_{H,H}$ = 4.8 Hz, 4 H, H_β), 7.98 (dd, $^3J_{H,H}$ = 7.8, $^4J_{H,H}$ = 1.5 Hz, 4 H, *o*-Ph), 7.71–7.65 (m, 6 H, *m*+*p*-Ph), 7.62 (d, $^3J_{H,H}$ = 7.8 Hz, 4 H, *o*-Bn), 7.43 (t, $^3J_{H,H}$ = 7.5 Hz, 4 H, *m*-Bn), 7.38 (t, $^3J_{H,H}$ = 7.5 Hz, 2 H, *p*-Bn), 5.66 (s, 4 H, OCH_2-Ph) ppm. UV/Vis ($CHCl_3$): λ = 416, 529, 561 (sh) nm. HRMS (ESI): *m*/*z* calcd. for $C_{46}H_{32}N_4NaNiO_2$ $[M + Na]^+$ 753.17710; found 753.17891.

(5-Bromo-15-hexyloxy-10,20-diphenylporphyrinato)nickel(II) (Ni-2f): (Table 1, entry 10): Prepared by following the general procedure from Ni-**1** and hexyl alcohol (498 mg, 612 μL, 4.88 mmol, 66 equiv.) in diglyme, yield 57%; red solid. ^{1}H NMR (600 MHz, $CDCl_3$, 25 °C): δ = 9.40 (d, $^3J_{H,H}$ = 5.0 Hz, 2 H, H_β), 9.29 (d, $^3J_{H,H}$ = 4.9 Hz, 2 H, H_β), 8.70 (d, $^3J_{H,H}$ = 5.0 Hz, 2 H, H_β), 8.68 (d, $^3J_{H,H}$ = 4.9 Hz, 2 H, H_β), 7.93–7.96 (m, 4 H, *o*-Ph), 7.72–7.64 (m, 6 H, *m*+*p*-Ph), 4.58 (t, $^3J_{H,H}$ = 6.5 Hz, 2 H, CH_2), 2.04 (tt, $^3J_{H,H}$ = 7.9, $^3J_{H,H}$ = 6.5 Hz, 2 H, CH_2), 1.67 (quint, $^3J_{H,H}$ = 7.9 Hz, 2 H, CH_2), 1.33–1.42 (m, 4 H, CH_2), 0.91 (t, $^3J_{H,H}$ = 7.1 Hz, 3 H, CH_3) ppm. UV/Vis ($CHCl_3$): λ = 418, 532, 565 (sh) nm. HRMS (ESI): *m*/*z* calcd. for $C_{38}H_{32}BrN_4NiO$ $[M + H]^+$ 696.10292; found 696.10488.

Demetallation of Ni-2f; Route 1: Ni-**2f** (5 mg, 7 μmol) was dissolved in CH_2Cl_2 (5 mL) and H_2SO_4 (50 μL) was added upon vigorous stirring (the mixture became green). After stirring at ambient temperature for 15 min, water (5 mL) was added and the reaction mixture was neutralized (pH 7) by using saturated aqueous $NaHCO_3$. The organic layer was separated and analyzed by MALDI-TOF MS. A mixture of 2H-**2f** (*m*/*z* 641.35) and 2H-**4f** (*m*/*z* 563.18) in a 1:1 ratio was obtained. The products were not separated.

Route 2: Ni-**2f** (5 mg, 7 μmol) was dissolved in $CHCl_3$ (5 mL) and TFA (100 μL) was added upon stirring. The progress of the reaction was monitored by UV/Vis and MALDI-TOF MS. No conversion of the starting material was detected after 5 h.

[5-Bromo-15-hexyloxy-10,20-diphenylporphyrinato]zinc(II) (Zn-2f): (Table 2, entry 5): A 10 mL flask containing the starting Zn-**1** (20 mg, 0.03 mmol) and Cs_2CO_3 (29 mg, 0.09 mmol) was evacuated and backfilled with argon three times. DMA (3.75 mL) and hexanol (0.25 mL, 66 equiv.) were then added and the mixture was heated under argon for 15 h. After cooling to room temperature, the reaction mixture was diluted with $CHCl_3$ (10 mL), filtered, and the solvents were evaporated under reduced pressure at 60 °C. The residue was purified by chromatography on silica gel ($CHCl_3$/hexane, 0→50%). The product was purified by using preparative TLC on silica gel (hexane/acetone, 4:1), yield 49%; violet solid. ^{1}H NMR (300 MHz, $CDCl_3$, 25 °C): δ = 9.62 (d, $^3J_{H,H}$ = 4.8 Hz, 2 H, H_β), 9.30 (d, $^3J_{H,H}$ = 4.8 Hz, 2 H, H_β), 8.89 (d, $^3J_{H,H}$ = 4.7 Hz, 2 H, H_β), 8.84 (d, $^3J_{H,H}$ = 4.5 Hz, 2 H, H_β), 8.12 (m, 4 H, *o*-Ph), 7.77 (t, $^3J_{H,H}$ = 7.3 Hz, 2 H, *p*-Ph), 7.73 (t, $^3J_{H,H}$ = 7.3 Hz, 4 H, *m*-Ph), 4.80 (t, $^3J_{H,H}$ = 6.9 Hz, 2 H, CH_2), 2.21 (m, 2 H, CH_2), 1.78 (m, 2 H, CH_2), 1.52–1.43 (m, 4 H, CH_2), 0.97 (t, $^3J_{H,H}$ = 7.2 Hz, 3 H, Me) ppm. UV/Vis ($CHCl_3$): λ = 425, 556, 602 nm. HRMS (ESI): *m*/*z* calcd. for $C_{38}H_{31}BrN_4OZn$ $[M]^+$ 702.09672; found 702.09865.

The reaction conditions were optimized in a series of experiments reported in Table 2 (entries 1–5). All reactions were performed according to this procedure and monitored by NMR spectroscopy or by MALDI-TOF MS.

[5,15-Bis(hexyloxy)-10,20-diphenylporphyrinato]zinc(II) (Zn-3f): (Table 2, entry 6): A 25 mL flask containing Zn-**1** (50 mg, 0.074 mmol) was evacuated and backfilled with argon three times. Hexanol (10 mL) and MeOLi (2 M in hexanol, 3.7 mL, 100 equiv.) were added and the mixture was heated to reflux for 1 h. After cooling to room temperature, the mixture was diluted with $CHCl_3$ (10 mL) and quenched with water (10 mL). The organic layer was separated and the solvents evaporated under reduced pressure at 60 °C. The residue was separated by column chromatography on silica gel ($CHCl_3$/hexane 0→50%), yields: 24% (Zn-**3f**) and 42% (Zn-**4f**); violet solids.

The reaction was also performed using 10 equiv. of MeOLi (Table 2, entry 7). However, the target product Zn-**3f** was obtained in low yield (8%) along with porphyrins Zn-**4f** and Zn-**8.**

The spectroscopic data of Zn-**3f** and Zn-**8** were in good agreement with reported data.[26]

Compound Zn-4f: ^{1}H NMR (300 MHz, $CDCl_3$, 25 °C): δ = 10.06 (s, 1 H, H_{meso}), 9.54 (d, $^3J_{H,H}$ = 4.5 Hz, 2 H, H_β), 9.28 (d, $^3J_{H,H}$ = 4.5 Hz, 2 H, H_β), 9.01 (d, $^3J_{H,H}$ = 4.4 Hz, 2 H, H_β), 8.97 (d, $^3J_{H,H}$ = 4.5 Hz, 2 H, H_β), 8.20 (m, 4 H, *o*-Ph), 7.80–7.73 (m, 6 H, *m*+*p*-Ph), 5.00 (t, $^3J_{H,H}$ = 6.6 Hz, 2 H, CH_2O), 2.35 (m, 2 H, CH_2), 1.88 (m, 2 H, CH_2), 1.55 (m, 2 H, CH_2), 1.49 (m, 2 H, CH_2), 0.99 (t, $^3J_{H,H}$ = 7.2 Hz, 3 H, CH_3) ppm. UV/Vis ($CHCl_3$): λ = 415, 544, 585 nm. MS (MALDI-TOF): *m*/*z* calcd. for $C_{38}H_{34}N_4OZn$ $[M]^+$ 624.19; found 624.60. HRMS (ESI): *m*/*z* calcd. for $C_{38}H_{34}N_4OZn$ $[M]^+$ 624.18621; found 624.18581.

S_NAr Reactions of Free-Base Porphyrin 2H-1 and 2H-8 with Alcohols

5,15-Bis(hexyloxy)-10,20-diphenylporphyrin (2H-3f): (Table 3, entry 4): A 25 mL flask, charged with 2H-**1** (50 mg, 0.08 mmol) and Cs_2CO_3 (79 mg, 0.24 mmol) was evacuated and backfilled with argon three times. 1-Hexanol (10 mL) was added and the mixture was heated under argon for 1 h. After cooling to room temperature, the reaction mixture was filtered through a short pad of neutral alumina using $CHCl_3$ as an eluent. The eluent was evaporated and the product was purified by column chromatography on silica gel ($CHCl_3$/hexane, 0→50%). Porphyrins 2H-**3f** and 2H-**4f** were obtained as a mixture and separated by preparative TLC (hexane/acetone, 4:1), yields: 86% (2H-**3f**) and 9% (2H-**4f**); violet solids.

The spectroscopic data of 2H-**3f** were in good agreement with reported data.[26]

Compound 2H-4f: ^{1}H NMR (600 MHz, $CDCl_3$, 25 °C): δ = 10.05 (s, 1 H, H_{meso}), 9.55 (d, $^3J_{H,H}$ = 4.6 Hz, 2 H, H_β), 9.24 (d, $^3J_{H,H}$ = 4.6 Hz, 2 H, H_β), 8.96 (d, $^3J_{H,H}$ = 4.6 Hz, 2 H, H_β), 8.91 (d, $^3J_{H,H}$ = 4.6 Hz, 2 H, H_β), 8.22 (m, 4 H, *o*-Ph), 7.80–7.75 (m, 6 H, *m*+*p*-Ph), 5.04 (t, $^3J_{H,H}$ = 6.6 Hz, 2 H, CH_2O), 2.39 (m, 2 H, CH_2), 1.91 (m, 2 H, CH_2), 1.56 (m, 2 H, CH_2), 1.50 (m, 2 H, CH_2), 0.99 (t, $^3J_{H,H}$ = 7.2 Hz, 3 H, CH_3), –2.80 (s, 2 H, NH) ppm. UV/Vis ($CHCl_3$): λ = 413, 510, 546, 586, 641 nm. HRMS (ESI): *m*/*z* calcd. for $C_{38}H_{35}N_4O$ $[M + H]^+$ 563.28054; found 563.28004.

The reaction was also performed using Na_2CO_3 as a base under similar conditions. The reagent amounts, the temperature, and the reaction times are reported in Table 3 (entries 5 and 6). The reactions were monitored by MALDI-TOF MS and did not afford the target product.

5-Bromo-15-hexyloxy-10,20-diphenylporphyrinate (2H-2f): (Table 3, entry 3). 2H-**1** (50 mg, 0.080 mmol) and Na_2CO_3 (61 mg, 0.240 mmol) were heated in 1-hexanol (10 mL) at 170 °C under dry argon for 24 h. After cooling to room temperature, the reaction mixture was filtered through a short pad of neutral alumina using $CHCl_3$ as eluent. The solvent was evaporated and the product was purified by column chromatography on silica gel ($CHCl_3$/hexane, 0→50%; the fraction containing 2H-**2f** was collected at 25→50% $CHCl_3$/hexane), yield 64%. ^{1}H NMR (600 MHz, $CDCl_3$, 25 °C): δ = 9.59 (d, $^3J_{H,H}$ = 4.8 Hz, 2 H, H_β), 9.44 (d, $^3J_{H,H}$ = 4.6 Hz, 2 H, H_β), 8.84 (d, $^3J_{H,H}$ = 4.8 Hz, 2 H, H_β), 8.80 (d, $^3J_{H,H}$ = 4.6 Hz, 2 H, H_β), 8.17 (m, 4 H, *o*-Ph), 7.81–7.73 (m, 6 H, *m*+*p*-Ph), 5.00 (t, $^3J_{H,H}$ = 6.6 Hz, 2 H, CH_2), 2.35 (m, 2 H, CH_2), 1.88 (m, 2 H, CH_2), 1.57–1.44 (m, 4 H, CH_2), 0.99 (t, $^3J_{H,H}$ = 7.2 Hz, 3 H, Me), –2.63 (s, 2 H, NH) ppm. UV/Vis ($CHCl_3$): λ = 420, 520, 557, 600, 657 nm. MS (MALDI-TOF): *m*/*z* calcd. for $C_{38}H_{34}BrN_4O$ $[M]^+$ 641.19; found 641.26.

The reaction conditions were optimized in a series of experiments reported in Table 3 (entries 1–3). All reactions were performed according to this procedure and monitored by MALDI-TOF MS.

5,15-Bis(hexadecyloxy)-10,20-diphenylporphyrinate (2H-3g) and 5-Bromo-15-hexadecyloxy-10,20-diphenylporphyrinate (2H-2g) Mixture (11:1): A 25 mL flask charged with 2H-**1** (50 mg, 0.080 mmol), Cs_2CO_3 (79 mg, 0.240 mmol) and hexadecanol (8.25 g) was evacuated and backfilled with argon three times and the mixture was heated at 170 °C for 1 h. After cooling to room temperature, the reaction mixture was filtered through a short pad of neutral alumina using $CHCl_3$ as an eluent. The eluent (ca. 50 mL) was evaporated and the product was purified by column chromatography on silica gel ($CHCl_3$/hexane, 0→50%). The fraction containing a mixture of porphyrins 2H-**2g** and 2H-**3g** (1:11) and hexadecyl alcohol was collected with a binary solvent mixture containing 25–50% of $CHCl_3$, yield 88%.

Compound 2H-3g: Obtained as a mixture with 2H-**2g** and hexadecyl alcohol. ^{1}H NMR (600 MHz, $CDCl_3$, 25 °C): δ = 9.45 (d, $^3J_{H,H}$ = 4.6 Hz, 4 H, H_β), 8.83 (d, $^3J_{H,H}$ = 4.6 Hz, 4 H, H_β), 8.17 (d, $^3J_{H,H}$ = 6.7 Hz, 4 H, *o*-Ph), 7.81–7.73 (m, 6 H, *m*+*p*-Ph), 5.03 (t, $^3J_{H,H}$ = 6.7 Hz, 4 H, CH_2O) ppm. Other aliphatic resonances overlapped with the signals of hexadecyl alcohol protons.

A mixture of 2H-**2g** and 2H-**3g** was inseparable by chromatography on silica gel or alumina. The pure products were obtained after the metallation/demetallation of the porphyrins according to the following procedure:

The mixture of 2H-**2g** and 2H-**3g** was dissolved in $CHCl_3$/MeOH (1:1, 5 mL) and solid $Zn(OAc)_2$ (29 mg, 0.16 mmol) was added to this solution. The reaction mixture was stirred at room temperature until complete conversion of the free-base porphyrins according to UV/Vis spectroscopy was observed (ca. 30 min). The reaction mixture was evaporated under reduced pressure and the product was purified by preparative TLC (hexane/acetone, 4:1), yields: 82% (Zn-**3g**) and 6% (Zn-**2g**); violet solids.

To obtain free-base porphyrin 2H-**2g**, Zn-**2g** was demetallated according to the following procedure**.** Complex Zn-**2g** was dissolved in 1% TFA in $CHCl_3$ (5 mL) and stirred at room temperature for 15 min. Water (5 mL) was then added to the green solution and the obtained biphasic mixture was neutralized to pH 7 by dropwise addition of saturated aqueous $NaHCO_3$. The organic layer was separated, dried with Na_2SO_4, and evaporated under reduced pressure to give free-base porphyrin 2H-**2g**, yield 99%.

Compound Zn-2g: ^{1}H NMR (300 MHz, $CDCl_3$, 25 °C): δ = 9.67 (d, $^3J_{H,H}$ = 4.4 Hz, 2 H, H_β), 9.45 (d, $^3J_{H,H}$ = 4.3 Hz, 2 H, H_β), 8.92 (d, $^3J_{H,H}$ = 4.4 Hz, 2 H, H_β), 8.88 (d, $^3J_{H,H}$ = 4.3 Hz, 2 H, H_β), 8.21–8.13 (m, 4 H, *o*-Ph), 7.81–7.71 (m, 6 H, *m*+*p*-Ph), 4.94 (t, $^3J_{H,H}$ = 6.2 Hz, 2 H, CH_2O), 2.31 (m, 2 H, CH_2), 1.84 (m, 2 H, CH_2), 1.53 (m, 2 H, CH_2), 1.43 (m, 2 H, CH_2), 1.38–1.18 (m, 20 H, CH_2), 0.85 (t, $^3J_{H,H}$ = 7.1 Hz, 3 H, CH_3) ppm. UV/Vis ($CHCl_3$): λ = 426, 561, 602 nm. MS (MALDI-TOF): *m*/*z* calcd. for $C_{48}H_{51}BrN_4OZn$ $[M]^+$ 842.25; found 842.21. HRMS (ESI): *m*/*z* calcd. for $C_{48}H_{51}BrN_4OZn$ $[M]^+$ 842.25322; found 842.25471.

Compound Zn-3g: ^{1}H NMR (600 MHz, $CDCl_3$, 25 °C): δ = 9.48 (d, $^3J_{H,H}$ = 4.6 Hz, 4 H, H_β), 8.90 (d, $^3J_{H,H}$ = 4.6 Hz, 4 H, H_β), 8.18 (m, 4 H, *o*-Ph), 7.79–7.71 (m, 6 H, *m*+*p*-Ph), 4.97 (t, $^3J_{H,H}$ = 6.6 Hz, 2 H, CH_2O), 2.35 (m, 2 H, CH_2), 1.87 (m, 2 H, CH_2), 1.55 (m, 2 H, CH_2), 1.44 (m, 2 H, CH_2), 1.36 (m, 2 H, CH_2), 1.33–1.19 (m, 18 H, CH_2), 0.85 (t, $^3J_{H,H}$ = 7.0 Hz, 3 H, CH_3) ppm. UV/Vis ($CHCl_3$): λ = 426, 561, 602 nm. MS (MALDI-TOF): *m*/*z* calcd. for $C_{64}H_{84}N_4O_2Zn$ $[M]^+$ 1004.59; found 1004.57.

Compound 2H-2g: ^{1}H NMR (600 MHz, $CDCl_3$, 25 °C): δ = 9.59 (d, $^3J_{H,H}$ = 4.7 Hz, 2 H, H_β), 9.44 (d, $^3J_{H,H}$ = 4.6 Hz, 2 H, H_β), 8.84 (d, $^3J_{H,H}$ = 4.7 Hz, 2 H, H_β), 8.79 (d, $^3J_{H,H}$ = 4.6 Hz, 2 H, H_β), 8.20–8.15 (m, 4 H, *o*-Ph), 7.80–7.73 (m, 6 H, *m*+*p*-Ph), 4.99 (t, $^3J_{H,H}$ = 6.6 Hz, 2 H, CH_2O), 2.35 (m, 2 H, CH_2), 1.86 (m, 2 H, CH_2), 1.54 (m, 2 H, CH_2), 1.44 (m, 2 H, CH_2), 1.36 (m, 2 H, CH_2), 1.32–1.19 (m, 18 H, CH_2), 0.85 (t, $^3J_{H,H}$ = 7.0 Hz, 3 H, CH_3), –2.65 (s, 2 H, NH) ppm. UV/Vis ($CHCl_3$): λ = 420, 520, 557, 600, 657 nm. HRMS (ESI): *m*/*z* calcd. for $C_{48}H_{54}BrN_4O$ $[M + H]^+$ 781.34755; found 781.34817.

5-Hexyloxy-10,20-diphenylporphyrin (2H-4f): Compound 2H-**8** (29 mg, 0.054 mmol) and Cs_2CO_3 (53 mg, 0.162 mmol) were heated in 1-hexanol (7.4 mL) at 170 °C for 1.5 h under dry argon. After cooling to room temperature, the reaction mixture was filtered through a short pad of neutral alumina using $CHCl_3$ as eluent. The eluent was concentrated under reduced pressure and purified by chromatography on silica gel ($CHCl_3$/hexane, 0→50%; the fraction containing 2H-**4f** was collected at 25→50% of $CHCl_3$/hexane), yield 52%; violet solid. The spectroscopic data of 2H-**4f** were in good agreement with the data described above.

Pd-Catalyzed Cross-Coupling Reactions of Ni-2f

[5-Hexyloxy-15-(4-formylphenyl)-10,20-diphenylporphyrinato]-nickel(II) (Ni-5f): A 10 mL flask containing Ni-**2f** (28 mg, 0.04 mmol), 4-pinacolborane-benzaldehyde (19 mg, 0.08 mmol), $Pd(PPh_3)_4$ (10 mg, 20 mol-%) and Cs_2CO_3 (26 mg, 0.08 mmol) was evacuated and backfilled with N_2 three times. Toluene (2 mL) was then added by using a syringe and the reaction mixture was stirred and heated to reflux for 19 h and then cooled to room temperature. After evaporation under reduced pressure, the residue was purified by chromatography on silica gel (CH_2Cl_2/heptane, 0→100%), yield 62%; red solid. ^{1}H NMR (300 MHz. $CDCl_3$, 25 °C): δ = 10.27 (s, 1 H, CHO), 9.37 (d, $^3J_{H,H}$ = 4.9 Hz, 2 H, H_β), 8.76 (d, $^3J_{H,H}$ = 4.9 Hz, 2 H, H_β), 8.70 (d, $^3J_{H,H}$ = 5.0 Hz, 2 H, H_β), 8.57 (d, $^3J_{H,H}$ = 5.0 Hz, 2 H, H_β), 8.14 (s, 4 H, Ar), 8.02–7.95 (m, 4 H, *o*-Ph), 7.71–7.62 (m, 6 H, *m*+*p*-Ph), 4.64 (t, $^3J_{H,H}$ = 6.7 Hz, 2 H, CH_2O), 2.08 (tt, $^3J_{H,H}$ = 7.6, $^3J_{H,H}$ = 6.7 Hz, 2 H, CH_2), 1.77–1.60 (m, 4 H, $2CH_2$), 1.45–1.37 (m, 2 H, CH_2), 0.93 (t, $^3J_{H,H}$ = 7.0 Hz, 3 H, CH_3) ppm. UV/Vis ($CHCl_3$): λ = 417, 530 nm. MS (MALDI-TOF): *m*/*z* calcd. for $C_{45}H_{36}N_4NiO_2$ $[M]^+$ 722.22; found 722.08. HRMS (ESI): *m*/*z* calcd. for $C_{45}H_{36}N_4NiO_2$ $[M]^+$ 722.21973; found 722.21863.

[5-Hexyloxy-15-(2-trimethylsilylacetylenyl)-10,20-diphenylporphyrinato]nickel(II) (Ni-6f): A 10 mL flask charged with Ni-**2f** (28 mg, 0.04 mmol), $Pd(PPh_3)_2Cl_2$ (3.4 mg, 12 mol-%), and CuI (1 mg, 13 mol-%) was evacuated and backfilled with N_2 three times. Toluene (1.7 mL), Et_3N (0.3 mL), and trimethylsilylacetylene (0.18 mL, 0.79 mmol) were then added by using syringes and the mixture was heated to reflux for 15 h, cooled to room temperature, evaporated under reduced pressure and purified by column chromatography on silica gel (CH_2Cl_2/heptane, 0→50%), yield: 63%; deep-red solid. Nickel(II) 5,15-diphenyl-10,20-bis(2-trimethylsilylacetilenyl)porphyrinate (Ni-**9**) was also isolated as a deep-red solid (13% yield).

Compound Ni-6f: ^{1}H NMR (300 MHz, $CDCl_3$, 25 °C): δ = 9.42 (d, $^3J_{H,H}$ = 4.9 Hz, 2 H, H_β), 9.28 (d, $^3J_{H,H}$ = 4.9 Hz, 2 H, H_β), 8.71 (d, $^3J_{H,H}$ = 4.9 Hz, 2 H, H_β), 8.65 (d, $^3J_{H,H}$ = 4.9 Hz, 2 H, H_β), 8.00–7.93 (m, 4 H, *o*-Ph), 7.72–7.63 (m, 6 H, *m*+*p*-Ph), 4.62 (t, $^3J_{H,H}$ = 6.7 Hz, 2 H, CH_2O), 2.07 (tt, $^3J_{H,H}$ = 7.6, $^3J_{H,H}$ = 6.7 Hz, 2 H, CH_2), 1.69 (m, 2 H, CH_2), 1.45–1.36 (m, 4 H, 2 CH_2), 0.92 (t, $^3J_{H,H}$ = 6.9 Hz, 3 H, CH_3), 0.527 (s, 9 H, Me_3Si) ppm. UV/Vis ($CHCl_3$): λ = 425, 540, 566 (sh) nm. MS (MALDI-TOF): *m*/*z* calcd. for $C_{43}H_{40}N_4NiOSi$ $[M]^+$ 714.23; found 713.88. HRMS (ESI): *m*/*z* calcd. for $C_{43}H_{40}N_4NiOSi$ $[M]^+$ 714.23271; found 714.23194.

Compound Ni-9: ^{1}H NMR (300 MHz, $CDCl_3$, 25 °C): δ = 9.43 (d, $^3J_{H,H}$ = 4.9 Hz, 4 H, H_β), 8.69 (d, $^3J_{H,H}$ = 4.9 Hz, 4 H, H_β), 7.99–7.92 (m, 4 H, *o*-Ph), 7.72–7.65 (m, 6 H, *m*+*p*-Ph), 0.51 (s, 18 H, 2 × Me_3Si) ppm. UV/Vis ($CHCl_3$): λ = 432, 554, 590 nm. MS (MALDI-TOF): *m*/*z* calcd. for $C_{42}H_{36}N_4NiSi_2$ 710.18; found 709.90. HRMS (ESI): *m*/*z* calcd. for $C_{42}H_{36}N_4NiSi_2$ 710.18347; found 709.18265.

[5-Hexyloxy-15-morpholino-10,20-diphenylporphyrinato]nickel(II) (Ni-7f): A 10 mL flask charged with Ni-**2f** (28 mg, 0.04 mmol), Pd_2dba_3 (1.8 mg, 5 mol-%), BINAP (5.3 mg, 20 mol-%), and Cs_2CO_3 (45 mg, 0.14 mmol) were evacuated and backfilled with N_2 three times, then toluene (2 mL) and morpholine (35 μL, 0.4 mmol) were added by using syringes. The mixture was heated to reflux for 18 h, then cooled to ambient temperature, evaporated under reduced pressure and applied to silica column (CH_2Cl_2/heptane, 0→100% and MeOH/CH_2Cl_2, 0→2%), yield 25% (ca. 90% purity); red solid. ^{1}H NMR (300 MHz, $CDCl_3$, 25 °C): δ = 9.39 (d, $^3J_{H,H}$ = 5.0 Hz, 2 H, H_β), 9.29 (d, $^3J_{H,H}$ = 5.0 Hz, 2 H, H_β), 8.70 (d, $^3J_{H,H}$ = 5.0 Hz, 2 H, H_β), 8.69 (d, $^3J_{H,H}$ = 5.0 Hz, 2 H, H_β), 7.99–7.94 (m, 4 H, *o*-Ph), 7.71–7.65 (m, 6 H, *m*+*p*-Ph), 4.58 (t, $^3J_{H,H}$ = 6.6 Hz, 2 H, CH_2O), 4.22 (br. t, $^3J_{H,H}$ = 4.4 Hz, 4 H, CH_2N), 4.04 (br. t, $^3J_{H,H}$ = 4.4 Hz, 4 H, CH_2N), 2.03 (tt, $^3J_{H,H}$ = 7.6, $^3J_{H,H}$ = 6.7 Hz, 2 H, CH_2), 1.67 (m, 2 H, CH_2), 1.38 (m, 4 H, 2 × CH_2), 0.90 (t, $^3J_{H,H}$ = 6.9 Hz, 3 H, CH_3) ppm. MS (MALDI-TOF): *m*/*z* calcd. for $C_{42}H_{39}N_5NiO_2$ $[M]^+$ 703.25; found 702.83.

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[1] S. J. Lee, J. T. Hupp, *Coord. Chem. Rev.* **2006**, *250*, 1710–1723.
[2] M. G. Walter, A. B. Rudine, C. C. Wamser, *J. Porphyrins Phthalocyanines* **2010**, *14*, 759–792.
[3] J. F. van Staden, R. I. S.-V. Staden, *Talanta* **2010**, *80*, 1598–1605.
[4] T. D. Mody, *J. Porphyrins Phthalocyanines* **2000**, *4*, 362–367.
[5] M. C. DeRosa, R. J. Crutchley, *Coord. Chem. Rev.* **2002**, *233*, 351–371.
[6] Y.-J. Cheng, S.-H. Yang, C.-S. Hsu, *Chem. Rev.* **2009**, *109*, 5868–5923.
[7] L.-L. Li, E. W.-G. Diau, *Chem. Soc. Rev.* **2012**, *42*, 291–304.
[8] J. V. Ruppel, K. B. Fields, N. L. Snyder, X. P. Zhang, in: *Handbook of Porphyrin Science* (Eds.: K. M. Kadish, K. M. Smith, R. Guilard), World Scientific Publishing, Singapore, **2011**, vol. 10, p. 1–84.
[9] *Synthesis and Modifications of Porphyrinoids* (Topic in Heterocyclic Chemistry, vol. 33) (Ed.: R. Paolesse), Springer Verlag, Berlin, Heidelberg, **2014**.
[10] I. P. Beletskaya, V. S. Tyurin, A. Uglov, C. Stern, R. Guilard, in: *Handbook of Porphyrin Science* (Eds.: K. M. Kadish, K. M. Smith, R. Guilard), World Scientific Publishing, Singapore, **2012**, vol. 23, p. 82–281.
[11] A. G. Bessmertnykh Lemeune, C. Stern, Y. G. Gorbunova, A. Y. Tsivadze, R. Guilard, *Macroheterocycles* **2014**, *7*, 122–132.
[12] J.-M. Camus, P. Harvey, R. Guilard, *Macroheterocycles* **2013**, *6*, 13–22.
[13] M. J. Crossley, L. G. King, J. L. Simpson, *J. Chem. Soc., Perkin Trans. 1* **1997**, 3087–3096.
[14] M. J. Crossley, L. G. King, *J. Chem. Soc., Perkin Trans. 1* **1996**, 1251–1260.
[15] L. C. Gong, D. Dolphin, *Can. J. Chem.* **1985**, *63*, 406–411.
[16] M. M. Catalano, M. J. Crossley, L. G. King, *J. Chem. Soc., Chem. Commun.* **1984**, 1537–1538.
[17] M. J. Crossley, L. G. King, S. M. Pyke, *Tetrahedron* **1987**, 4569–4577.
[18] M. J. Crossley, M. Harding, C. Tansey, *J. Org. Chem.* **1994**, *59*, 4433–4437.
[19] M. J. Crossley, L. King, S. Pyke, C. Tansey, *J. Porphyrins Phthalocyanines* **2002**, *6*, 685–694.
[20] M. C. Balaban, C. Chappaz-Gillot, G. Canard, O. Fuhr, C. Roussel, T. S. Balaban, *Tetrahedron* **2009**, *65*, 3733–3739.
[21] M. Balaban, A. Eichhöfer, G. Buth, R. Hauschild, J. Szmytkowski, H. Kalt, T. Balaban, *J. Phys. Chem. B* **2008**, *112*, 5512–5521.
[22] N. N. Sergeeva, M. O. Senge, A. Ryan, in *Handbook of Porphyrin Science* (Eds.: K. M. Kadish, K. M. Smith, R. Guilard), World Scientific Publishing, Singapore, **2010**, vol. 3, p. 325–365.
[23] K. B. Fields, J. V. Ruppel, N. L. Snyder, X. P. Zhang, in: *Handbook of Porphyrin Science* (Eds.: K. M. Kadish, K. M. Smith, R. Guilard), World Scientific Publishing, Singapore, **2010**, vol. 10, p. 367–427.
[24] Y. Matano, K. Matsumoto, Y. Terasaka, H. Hotta, Y. Araki, O. Ito, M. Shiro, T. Sasamori, N. Tokitoh, H. Imahori, *Chem. Eur. J.* **2007**, *13*, 891–901.
[25] Y. Matano, K. Matsumoto, H. Hayashi, Y. Nakao, T. Kumpulainen, V. Chukharev, N. V. Tkachenko, H. Lemmetyinen, S. Shimizu, N. Kobayashi, *J. Am. Chem. Soc.* **2012**, *134*, 1825–1839.
[26] G.-Y. Gao, A. J. Colvin, Y. Chen, X. P. Zhang, *Org. Lett.* **2003**, *5*, 3261–3264.
[27] C. Liu, D. M. Shen, Q. Y. Chen, *J. Org. Chem.* **2007**, *72*, 2732–2736.
[28] G.-Y. Gao, J. V. Ruppel, K. B. Fields, X. Xu, Y. Chen, X. P. Zhang, *J. Org. Chem.* **2008**, *73*, 4855–4858.
[29] Q. Chen, Y.-Z. Zhu, Q.-J. Fan, S.-C. Zhang, J.-Y. Zheng, *Org. Lett.* **2014**, *16*, 1590–1593.
[30] T. Takanami, S. Hayashi, K. Iso, J. Matsumoto, F. Hino, *Tetrahedron Lett.* **2011**, *52*, 5345–5348.
[31] K.-I. Yamashita, K. Kataoka, M. S. Asano, K.-I. Sugiura, *Org. Lett.* **2012**, *14*, 190–193.
[32] C. H. Devillers, S. Hebié, D. Lucas, H. Cattey, S. Clément, S. Richeter, *J. Org. Chem.* **2014**, *79*, 6424–6434.
[33] A. A. Ryan, S. Plunkett, A. Casey, T. McCabe, M. O. Senge, *Chem. Commun.* **2014**, *50*, 353–355.
[34] H. R. A. Golf, H.-U. Reissig, A. Wiehe, *Eur. J. Org. Chem.* **2015**, 1548–1568.
[35] Y. Chen, G.-Y. Gao, X. P. Zhang, *Tetrahedron Lett.* **2005**, *46*, 4965–4969.
[36] S. G. DiMagno, V. S. Y. Lin, M. J. Therien, *J. Org. Chem.* **1993**, *58*, 5983–5993.
[37] D. P. Arnold, R. C. Bott, H. Eldridge, F. M. Elms, G. Smith, M. Zojaji, *Aust. J. Chem.* **1997**, *50*, 495–503.
[38] R. Gujadhur, D. Venkataraman, *Synth. Commun.* **2001**, *31*, 2865–2879.
[39] R. G. R. Bacon, S. C. Rennison, *J. Chem. Soc., C* **1969**, 308.
[40] M. Zeng, Y. Du, L. Shao, C. Qi, X.-M. Zhang, *J. Org. Chem.* **2010**, *75*, 2556–2563.
[41] H. Sakurai, T. Sanji, *European patent*, **2003**, EP1489063A1.
[42] J. Mack, N. Kobayashi, Z. Shen, in: *Handbook of Porphyrin Science* (Eds.: K. M. Kadish, K. M. Smith, R. Guilard), World Scientific Publishing, Singapore, **2012**, vol. 23, p. 281–371.
[43] C. M. B. Carvalho, M. G. P. M. S. Neves, A. C. Tome, F. A. A. Paz, A. M. S. Silva, J. A. S. Cavaleiro, *Org. Lett.* **2011**, *13*, 130–133.
[44] A. A. Sinelshchikova, S. E. Nefedov, Y. Y. Enakieva, Y. G. Gorbunova, A. Y. Tsivadze, K. M. Kadish, P. Chen, A. Bessmertnykh-Lemeune, C. Stern, R. Guilard, *Inorg. Chem.* **2013**, *52*, 999–1008.
[45] E. V. Vinogradova, Y. Y. Enakieva, S. E. Nefedov, K. P. Birin, A. Y. Tsivadze, Y. G. Gorbunova, A. G. Bessmertnykh Lemeune, C. Stern, R. Guilard, *Chem. Eur. J.* **2012**, *18*, 15092–15104.
[46] Y. Y. Enakieva, A. G. Bessmertnykh, Y. G. Gorbunova, C. Stern, Y. Rousselin, A. Y. Tsivadze, R. Guilard, *Org. Lett.* **2009**, *11*, 3842–3845.
[47] R. I. Zubatyuk, A. A. Sinelshchikova, Y. Y. Enakieva, Y. G. Gorbunova, A. Y. Tsivadze, S. E. Nefedov, A. Bessmertnykh-Lemeune, R. Guilard, O. V. Shishkin, *CrystEngComm* **2014**, *16*, 10428–10438.
[48] M. A. Uvarova, A. A. Sinelshchikova, M. A. Golubnichaya, S. E. Nefedov, Y. Y. Enakieva, Y. G. Gorbunova, A. Y. Tsivadze, C. Stern, A. Bessmertnykh-Lemeune, R. Guilard, *Cryst. Growth Des.* **2014**, *14*, 5976–5984.
[49] M. L. Główka, D. Martynowski, K. Kozłowska, *J. Mol. Struct.* **1999**, *474*, 81–89.
[50] M. Pintea, M. O. Senge, *Tetrahedron Lett.* **2008**, *49*, 2236–2239.
[51] M. Yeung, A. C. H. Ng, M. G. B. Drew, E. Vorpagel, E. M. Breitung, R. J. McMahon, D. K. P. Ng, *J. Org. Chem.* **1998**, *63*, 7143–7150.

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