

Chemistry Europe

European Chemical

Societies Publishing



Accepted Article online prior to editing, proofing, and formal publication of the final Version of Record (VoR). This work is currently citable by using the Digital Object Identifier (DOI) given below. The VoR will be published online in Early View as soon as possible and may be different to this Accepted Article as a result of editing. Readers should obtain the VoR from the journal website shown below when it is published to ensure accuracy of information. The authors are responsible for the content of this Accepted Article.

To be cited as: Eur. J. Org. Chem. 10.1002/ejoc.202001174

Link to VoR: https://doi.org/10.1002/ejoc.202001174

WILEY-VCH

COMMUNICATION

WILEY-VCH

Oxidative Cyclodehydrogenation Reactions with Tetraarylporphyrins

Max M. Martin,^[a] Christoph Oleszak,^[a] Frank Hampel^[a] and Norbert Jux*^[a]

 [a] Dr. M. M. Martin, C. Oleszak, Dr. F. Hampel, Prof. Dr. N. Jux Department of Chemistry and Pharmacy & Interdisciplinary Center for Molecular Materials (ICMM), Chair of Organic Chemistry II Friedrich-Alexander-University Erlangen-Nuernberg Nikolaus-Fiebiger-Str. 10, 91058 Erlangen, Germany e-mai: max.martin@fau.de, norbert.jux@fau.de http://www.jux.chemie.nat.fau.de

Supporting information for this article is given via a link at the end of the document.

Abstract: The extension of the aromatic π -system of porphyrins is a powerful method to alter their optoelectronic properties. Herein, aryl substituents were fused to porphyrin cores by Scholl oxidation reactions that selectively produced mono- and doubly-fused porphyrins in yields of up to 69 %. Several different aryl substituents attached to the porphyrin were investigated with respect to their reactivity under Scholl conditions. The fused products were fully characterized, *i.e.*, by UV-vis absorption spectroscopy, which showed drastic changes in the electronic features. Insight into the solid-state behavior was obtained by X-ray crystallography. Our approach represents a novel option for the late-stage functionalization of porphyrin-based compounds.

The fusion of aromatic units to porphyrin cores has become a flourishing research area that generated a plethora of π -extended porphyrins.^[1-3] The extension of the chromophores' π -system represents an efficient tool to alter and therefore tailor the optical properties, e.g., the position of the absorption bands. For that, small polycyclic aromatic hydrocarbons (PAHs) such as benzene^[4-11] or anthracene^[12-15] but also larger ones such as nanographenes^[16-17] or graphene itself^[18] were fused once or several times to porphyrins. Typical synthesis procedures either use already π -extended pyrrole building blocks for porphyrin synthesis or fuse the desired aromatic units to pre-formed porphyrins afterwards.^[3] Especially the second concept, the postfusion of aromatics to porphyrins, established itself as the method of choice. Due to the versatility of this approach^[19-20] that relies on numerous suitable coupling possibilities, a huge π -extended porphyrin variety has already been prepared. For example, oxidative cyclodehydrogenation reactions, commonly known as Scholl oxidations,^[21] are frequently used to fuse aromatic building blocks to porphyrins.^[1-3] During our research, which is based on carbon-rich porphyrins,[22-30] we regularly expose porphyrins to oxidative Scholl conditions, yet we did not observe any fusion reactions up until recently. As long as the porphyrins are in their free base form, their core structure remains unaffected under standard Scholl conditions. Recently however, we subjected nickel porphyrins to Scholl conditions that resulted, instead of forming a PAH in the porphyrins' periphery, in a reaction between the aryl substituents and the porphyrin core.[29] Because the properties of the obtained product significantly differed to the ones of common porphyrins, e.g., the UV-vis absorption features, we

were curious whether Scholl oxidations might be a suitable tool for modifying the porphyrins' characteristics. This prompted us to further investigate the reactivity of porphyrins under oxidative aromatic coupling conditions, which will be presented in the following.

The first examples of π -extended porphyrins, in which mesophenyl substituents were fused to porphyrin cores, were prepared by an approach based on palladium catalysis.^[7-11] For that, suitable halogenated porphyrins were reacted to the respective π extended products with up to four fused phenyl rings per porphyrin core.^[10-11] Later on, Osuka and co-workers prepared similar π extended porphyrin motifs, however, via a different route. Their approach showed that 3,5-di-tert-butylphenyl substituted nickel porphyrins can be transformed to the respective π -extended derivatives under Scholl conditions.^[31-32] For example, nickel porphyrins 1 bearing different functional groups at one mesoposition were studied with respect to their reactivity behavior under Scholl conditions (Scheme 1).^[32] In their study, electron withdrawing substituents R attached to the porphyrin core lead to a regioselective formation of 10,12- and 18,20-doubly phenylenefused nickel porphyrins 2.[32]



Scheme 1. Synthesis of doubly-fused porphyrins **2** that were reported by Osuka and co-workers in 2016.^[32] R = NO₂, POPh₂, Bpin.

In our work, we approached the question about the reactivity of nickel porphyrins in Scholl reactions from a different perspective. Instead of studying the influence of one functional group, we were interested in the effect of the aryl substituents themselves. For that, our investigation started with a tetrakis(3,5-di-*tert*-butylphenyl) substituted nickel porphyrin **3** that was subjected to oxidative aromatic coupling conditions (Scheme 2). For the Scholl reaction, nickel porphyrin **3** was reacted with an excess amount of dry FeCl₃ (8 equiv.) in a CH₃NO₂/CH₂Cl₂ mixture. Under these

WILEY-VCH

COMMUNICATION

conditions, the C-C coupling reaction proceeded quickly and already after 1 h a new intensive olive spot was detected via TLC analysis (Scheme 2, left TLC). The reaction was stopped after 3 h and the crude product was purified by silica column chromatography. An olive green solid that was identified as the mono-fused porphyrin 4 was obtained in 69 % yield. During the end of the reaction, we realized that next to 4 another compound started to accumulate within the reaction mixture. We therefore tested different reaction conditions, in which more equivalents of FeCl₃ were added and allowed to react for a longer period of time. And indeed, after a reaction time of 23 h with 16 equiv. of FeCl₃ a new intensive red-brownish spot was detected next to the olive one of 4 via TLC analysis (Scheme 2, right TLC). After silica column chromatography, the red-brownish product was isolated (as well as 4) and identified as the doubly-fused porphyrin 5 (36 % yield). Although theoretically several different doubly-fused porphyrins exist, we only detected and isolated a single isomer (5) under the given reaction conditions. These results are in contrast to the previous results by the Osuka group.^[32] in which electron-withdrawing groups were accounted for the formation of doubly-fused isomers like 2 or 5. So far. attempts to synthesize triply- or quadruply-fused porphyrins with the herein reported procedure were unsuccessful.



 $\begin{array}{l} \textbf{Scheme 2. Scholl reaction of nickel porphyrin 3. a) FeCl_3 (8 equiv.), CH_3NO_2, \\ CH_2Cl_2, 3 h, rt; b) FeCl_3 (16 equiv.), CH_3NO_2, CH_2Cl_2, 23 h, rt. \\ \end{array}$

The fused porphyrin products **4** and **5** were unambiguously identified by NMR and UV-vis spectroscopic as well as mass spectrometric and X-ray crystallographic techniques. In the NMR spectra, the fusion of an aryl substituent to the adjacent β -position is clearly noticeable by an increased number of signals (Figure 1). For example, nickel porphyrin **3** shows 9 signals in the ¹³C NMR spectrum, whereas the mono-fused nickel porphyrin **4**, due to its reduced symmetry, has 48 separate carbon signals (Figure 1b). The fusion of a second bond to the doubly-fused system **5**, however, increases the symmetry again and therefore less signals with respect to **4** appear in the NMR spectrum (Figure S10).

Single crystals, suitable for X-ray crystallography were obtained for the starting material nickel porphyrin 3 as well as for the monoand doubly-fused nickel porphyrins 4 and 5, respectively (Figure 2). The crystals were grown out of CH₂Cl₂/MeOH (3, 5) or CH₂Cl₂/n-hexane/MeOH (4) solution mixtures. Initial attempts to crystallize the fused-porphyrins, however, failed because 4 and 5 showed an increased solubility behavior in organic solvents compared to porphyrin 3. Nevertheless, slow evaporation of the solvent mixture that is accompanied by a gradually increasing concentration yielded crystals with a suitable size and quality for X-ray diffraction experiments. A comparison between the structures of 3, 4 and 5 revealed significant differences in the solid-state characteristics. The molecules of nickel porphyrin 3 are, due to the steric demand of the 3,5-di-tert-butylphenyl substituents, only loosely packed (Figure 2d). The fusion of arvl substituents to porphyrin cores does not only extend the porphyrins' π -system but also reduces its overall steric demand. Hence, more dense packing structures are feasible. Therefore, mono- and doubly-fused porphyrins 4 and 5 feature the formation of dimers in the crystal with distances between the porphyrin cores^[33] of 4.22 Å and 3.30 Å for 4 and 5, respectively. The most pronounced interaction within the dimer was observed for the doubly-fused porphyrin 5, in which the two molecules almost completely overlap due to π - π interactions (Figure 2h). Furthermore, a short Ni-Ni distance of 3.51 Å was found for the dimers of 5. Additionally, a crystal structure of the free-base form of the doubly-fused porphyrin 5 was obtained (CCDC 2025049), which showed a similar dimer formation with porphyrin-porphyrin distances of 3.46 Å. For further information see supporting information Figure S4.



Figure 1. Comparison of NMR spectra of starting material porphyrin 3 and mono-fused porphyrin 4. a) ¹H NMR (400 MHz); b) ¹³C NMR (101 MHz).

CCCD

2

WILEY-VCH

COMMUNICATION



Figure 2. Single crystal X-ray structures of 3, 4 and 5. a) - c) Structures depicted as ORTEP models with thermal ellipsoids drawn at a 50 % probability. d) - h) Packing motif of the respective structures. a) - h) Solvent molecules are omitted for clarity. d) - h) Hydrogen atoms are removed for clarity. 3: CCDC 2025048; 4: CCDC 2025050; 5: CCDC 2025051.

The fusion of one or two aryl substituents to the porphyrin core significantly influences the electronic characteristics. The changes from **3** to the mono- and doubly-fused porphyrins **4** and **5** are recognizable by distinct color shifts from orange (**3**) to olive-green (**4**) to red-brownish (**5**). Additionally, fused nickel porphyrins **4** and **5** feature, compared to **3** as well as to other tetraarylporphyrins, a significantly more intensive color to the human eye. The changes of the electronic properties were studied by UV-vis absorption spectroscopy (Figure 3). The fusion of one aryl ring to the porphyrin core (**4**) leads to a drastic decrease of the molar extinction coefficient accompanied by a broadening of the porphyrins' B-band with strong absorption features in the range of 350 - 500 nm. The fusion of a second aryl ring (**5**) further broadens the B-band, which is leading almost to an absorption plateau in the range of 350 - 550 nm. Because molecules **4** and



Figure 3. UV-vis absorption spectra of nickel porphyrin 3 and mono- and doubly-fused nickel porphyrins 4 and 5 in CH_2CI_2 . The maximum absorption band of each spectrum is labeled.

5 absorb light in such a large window of the visible region their color intensity appears so strong.

After fusing the 3,5-di-*tert*-butylphenyl substituents once (4) and twice (5) to the porphyrin core we started to test other aryl substituents under Scholl conditions. For that, 4-*tert*-butylphenyl and 4-bromophenyl substituents as well as mesityl as a control group were chosen and reacted (Table 1). For meaningful results, all reactions were performed under the exact same conditions and tightly followed by TLC analysis. The only variable was the reaction time. As a consequence, the chosen reaction conditions are a compromise that allow suitable reactivity for all porphyrins but do not represent optimized conditions for the individual compounds. The isolated products were identified by NMR spectroscopy and mass spectrometry. Reactivity for all porphyrins under the given conditions was observed, however, at significantly different reaction rates (compare Table 1). The

fastest reaction was observed for the 3,5-ditert-butylphenyl substituted porphyrin 3, followed by the 4-tert-butylphenyl substituted porphyrin 6. The 4-bromophenyl substituted porphyrin 7 showed, similar to 3 and 6, the formation of a fused product that was observed by TLC analysis (olive green spot). The reaction of 7, however, seemed to proceed even slower and less smoothly than the ones of 3 and 6. As a result, significant amounts of byproduct were formed during the reaction of 7, which could not be separated from the desired fused product. Hence, no clear characterization of the product and determination of the yield could be performed. Finally, the mesityl control group porphyrin 8, which has no available positions for a fusion reaction, was tested. As expected, no fusion of the aryl substituent occurred but instead, a

ccepted Manuscrii

COMMUNICATION

partial chlorination of the porphyrins was observed by mass spectrometry (Figure S22).

Table 1. Reactivity comparison of different aryl substituents at the porphyrin. All reactions were started at the same day under the same conditions: Nickel porphyrin (50 µmol, 1 equiv.), FeCl₃ (800 µmol, 16. equiv.), CH₃NO₂ (1 mL), CH₂Cl₂ (10 mL), rt. For details see supporting information.

reaction no.	Ar Ar Ni Ar	reaction product	reaction time	isolated yield
1	Ar ₁ = -t-Su 3 t-Bu	1x fused	2.5 h	54 %
2	Ar ₁ = -t	2x fused	23 h	36 %
3	Ar₂ = -} 6	1x fused	43 h	64 %
4	Ar ₃ = - } →Br 7	1x fused	> 43 h	1
5		chlorinated	43 h	/

To conclude, the successful preparation of π -extended porphyrins by a fusion reaction of the aryl substituents to the porphyrin cores was presented. Standard FeCl₃ mediated Scholl conditions have proven to be suitable for the fusion of 3,5-di-tert-butylphenyl as well as 3-tert-butylphenyl substituents to the respective porphyrin core. Chlorination, which is a typical side reaction, only occurred for the control group, the mesityl substituted porphyrin 8 that cannot undergo a fusion reaction.

Finally, we like to emphasize the advantage of the herein presented concept: With our protocol, simple A₄-symmetric porphyrins, which can be easily prepared in decent yields and quantities, can be transformed to newly π -extended dyes using well-established reaction conditions. Due to this simplicity and the reliance on standard reactions, we think that this concept has a great potential for the preparation and application of exciting new dye materials. Additionally, this protocol is suitable for the late stage modification of many already existing porphyrin arrays. For example, the absorption characteristics of porphyrin-based light absorbing arrays might be improved and therefore higher efficiencies of photovoltaic devices could be achieved.^[34-36] The only limiting factor is that the substituents and functional groups attached to the porphyrin must be tolerant to Scholl conditions. To fully reveal the potential of this concept, fusing aryl substituents to porphyrins by Scholl reactions are currently under further investigation in our group.

Acknowledgements

Funded by the Deutsche Forschungsgemeinschaft (DFG) -Projektnummer 182849149 - SFB 953. M.M.M. thanks the Fonds der Chemischen Industrie (FCI) and the Graduate School Molecular Science (GSMS) for financial support.

Keywords: *π*-extension • porphyrinoids • fusion reaction • Scholl oxidation • post-functionalization

- J. P. Lewtak, D. T. Gryko, Chem. Commun. 2012, 48, 10069-[1]
- H. Mori, T. Tanaka, A. Osuka, J. Mater. Chem. C 2013, 1, 2500-[2] 2519
- M. Stępień, E. Gońka, M. Żyła, N. Sprutta, Chem. Rev. 2017, 117, [3] 3479-3716
- R. B. M. Koehorst, J. F. Kleibeuker, T. J. Schaafsma, D. A. de Bie, [4] B. Geurtsen, R. N. Henrie, H. C. van der Plas, J. Chem. Soc., Perkin Trans. 2 1981, 1005-1009
- S. Ito, T. Murashima, N. Ono, H. Uno, Chem. Commun. 1998, [5] 1661-1662
- M. Ruppel, D. Lungerich, S. Sturm, R. Lippert, F. Hampel, N. Jux, [6] Chem. Eur. J. 2020, 26, 3287-3296.
- S. Fox, R. W. Boyle, Chem. Commun. 2004, 1322-1323. D.-M. Shen, C. Liu, Q.-Y. Chen, Chem. Commun. 2005, 4982-[8]
- 4984 [9] D.-M. Shen, C. Liu, Q.-Y. Chen, J. Org. Chem. 2006, 71, 6508-6511
- [10] T. Ishizuka, Y. Saegusa, Y. Shiota, K. Ohtake, K. Yoshizawa, T. Kojima, Chem. Commun. 2013, 49, 5939-5941.
- [11] Y. Saegusa, T. Ishizuka, K. Komamura, S. Shimizu, H. Kotani, N. Kobayashi, T. Kojima, Phys. Chem. Chem. Phys. 2015, 17, 15001-15011.
- [12] H. Yamada, D. Kuzuhara, T. Takahashi, Y. Shimizu, K. Uota, T. Okujima, H. Uno, N. Ono, Org. Lett. 2008, 10, 2947-2950.
- V. Yakutkin, S. Aleshchenkov, S. Chernov, T. Miteva, G. Nelles, A. [13]
- Cheprakov, S. Baluschev, Chem. Eur. J. 2008, 14, 9846-9850. [14] N. K. Davis, A. L. Thompson, H. L. Anderson, Org. Lett. 2010, 12, 2124-2127.
- [15] N. K. S. Davis, A. L. Thompson, H. L. Anderson, J. Am. Chem. Soc. 2011, 133, 30-31.
- [16] Q. Chen, L. Brambilla, L. Daukiya, K. S. Mali, S. De Feyter, M. Tommasini, K. Müllen, A. Narita, Angew. Chem. Int. Ed. 2018, 57, 11233-11237
- [17] L. M. Mateo, Q. Sun, S. X. Liu, J. J. Bergkamp, K. Eimre, C. A Pignedoli, P. Ruffieux, S. Decurtins, G. Bottari, R. Fasel, T. Torres,
- Angew. Chem. Int. Ed. **2020**, 59, 1334-1339. Y. He, M. Garnica, F. Bischoff, J. Ducke, M.-L. Bocquet, M. Batzill, W. Auwärter, J. V. Barth, *Nat. Chem.* **2017**, 9, 33-38. [18]
- [19] A. Tsuda, A. Osuka, Science 2001, 293, 79-82.
- [20] V. V. Diev, K. Hanson, J. D. Zimmerman, S. R. Forrest, M. E.
- Thompson, Angew. Chem. Int. Ed. 2010, 49, 5523-5526. [21] M. Grzybowski, B. Sadowski, H. Butenschon, D. T. Gryko, Angew.
- Chem. Int. Ed. 2020, 59, 2998-3027. [22] J. M. Englert, J. Malig, V. A. Zamolo, A. Hirsch, N. Jux, Chem.
- Commun. 2013, 49, 4827-4829. D. Lungerich, J. F. Hitzenberger, M. Marcia, F. Hampel, T. [23]
 - Drewello, N. Jux, Angew. Chem. Int. Ed. 2014, 53, 12231-12235.
- D. Lungerich, J. F. Hitzenberger, W. Donaubauer, T. Drewello, N. [24] Jux, Chem. Eur. J. 2016, 22, 16755-16759.
- [25] M. M. Martin, N. Jux, J. Porphyrins Phthalocyanines 2018, 22, 454-460
- D. Lungerich, J. F. Hitzenberger, F. Hampel, T. Drewello, N. Jux, *Chem. Eur. J.* **2018**, *24*, 15818-15824. [26]
- [27] M. M. Martin, M. Dill, J. Langer, N. Jux, J. Org. Chem. 2019, 84, 1489-1499.
- M. M. Martin, D. Lungerich, P. Haines, F. Hampel, N. Jux, Angew. [28] Chem. Int. Ed. 2019, 58, 8932-8937.
- M. M. Martin, D. Lungerich, F. Hampel, J. Langer, T. K. Ronson, N. [29] Jux, Chem. Eur. J. 2019, 25, 15083-15090. [30]
 - M. M. Martin, C. Dusold, A. Hirsch, N. Jux, J. Porphyrins Phthalocyanines 2020, 24, 268-277.
- N. Fukui, W.-Y. Cha, S. Lee, S. Tokuji, D. Kim, H. Yorimitsu, A. [31] Osuka, Angew. Chem. Int. Ed. 2013, 52, 9728-9732.
- N. Fukui, S.-K. Lee, K. Kato, D. Shimizu, T. Tanaka, S. Lee, H. [32] Yorimitsu, D. Kim, A. Osuka, Chem. Sci. 2016, 7, 4059-4066.
- [33] A plane that was defined by the position of the four nitrogen atoms was calculated for each porphyrin. The distance between the porphyrin cores was determined by the distance between two calculated planes. [34]
 - H. Shinya, M. Yusuke, E. Seunghun, H. Hironobu, U. Tomokazu,
 - M. Yoshihiro, I. Hiroshi, Chem. Lett. 2008, 37, 846-847.
- [35] S. Hayashi, M. Tanaka, H. Hayashi, S. Eu, T. Umeyama, Matano, Y. Araki, H. Imahori, J. Phys. Chem. C 2008, 112, 15576-15585.
- [36] Y. Kurumisawa, T. Higashino, S. Nimura, Y. Tsuji, H. liyama, H. Imahori, J. Am. Chem. Soc. 2019, 141, 9910-9919.

WILEY-VCH

COMMUNICATION

Entry for the Table of Contents



The transformation of A₄-symmetric nickel porphyrins to the respective π -extended derivatives via a Scholl oxidative route is presented. Different *meso*-aryl substituents were successfully fused to the porphyrin core using standard Scholl conditions. The photophysical characteristics of fused-porphyrins were significantly different to the non-fused derivatives. Insight into the solid-state properties was obtained by X-ray crystallography.

Key-Topic

 π -extended porphyrins

Institute and/or researcher Twitter usernames: FAU_Germany, MaxMJCM