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Synthetic potential and limitations of *o*-quinones as acceptor groups in electron transfer compounds

Mathias O. Senge,* Sabine Hatscher, Zeynep Ökten and Marcus Speck

Institut für Chemie, Universität Potsdam, Karl-Liebknecht-Str. 24–25, D-14476 Golm, Germany

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Abstract—Syntheses have been developed that utilize *o*-quinones as suitable acceptor groups in porphyrin-based diad and triad donor–acceptor compounds. While alkyl groups at the 3,6-position of the quinone stabilize the target compounds, oxidative degradation and dimerization reactions can occur depending on the type of the porphyrin and quinone part. Thus, care has to be taken in choosing the right quinone and porphyrin component when designing novel electron transfer compounds.

Porphyrin quinones have served as standard compounds for studying and mimicking naturally occurring electron transfer (ET) processes such as the photoinduced ET.[1] However, almost exclusively *p*-quinones have been used as acceptor components in such systems due to the belief that the corresponding *o*-quinones are too reactive and unstable. Nevertheless, *o*-quinones can serve as acceptor groups in reconstituted native systems,[2] offer the benefit of a higher reduction potential, and allow a modulation of ΔG_{ET} by using the in situ formed semiquinones for metal chelatization.[3] In addition, they are important natural metabolites, enzyme cofactors and might have psychotomimetic properties.[4] In order to utilize the potential of *o*-quinones as acceptor groups, we[3,5] and others[6] have embarked on a program to develop appropriate synthetic strategies for porphyrin-*o*-quinone systems.

Our initial results showed that porphyrin-*o*-quinones can indeed be prepared in relative ease by standard acid-catalyzed condensation reactions of pyrrole **1** with appropriate aldehydes **3**. This required the use of 3,4-dimethoxybenzaldehydes **2** to introduce the '*o*-quinone' moiety[5] and yielded porphyrins of type **6** which could undergo demethylation reactions with BBr_3 to give porphyrin–quinone diads of type **7**. Although compounds like **7a** could be prepared and characterized their low stability necessitated the introduction of stabilizing substituents in the 3,6-positions of the quinone and compound **7b** was found to be stable and suitable for photophysical studies (Scheme 1). On the other hand, compound **7c** with a highly hindered *o*-quinone slowly degraded photochemically to muconic acid derivatives (**8**,**9**), products quite similar to those otherwise formed by catecholases.[7]

Thus, it became necessary to investigate if this is a general type of degradation reaction or if more complex donor–acceptor compounds with *o*-quinones are accessible by suitable variation of the substituents in the porphyrin and quinone part, respectively. In order to test the dependence of the quinone ring-opening reactions on the type of porphyrin, we synthesized the precursor porphyrins **6c**–**f**. Optimized Lindsey-type mixed condensations[8] (7 equiv. **3**, 8 equiv. **1**, 1 equiv. **2**) gave all compounds in low yields ranging from 1 to 4%. In order to improve the yields we prepared dipyrromethanes **4** of the quinone precursors and made a comprehensive study of various 2+2 condensation methods (1 equiv. **4**, 1 equiv. **5**, 2 equiv. **3**). Although these were unsuccessful for **6d**, condensations akin to those reported by Brückner et al.[9] allowed the synthesis of **6e** in 6.8% and gave an improved yield of 7% for **6c**.

Quite different reactivities were observed upon the demethylation of **6** to the porphyrin-*o*-quinone diads **7** in dependence on the substituent pattern in the porphyrin part. Various attempts to demethylate **6f** resulted in complete decomposition of the porphyrin, presumably due to the ease of oxidative reactions at the free *meso* positions. Both porphyrins with electron withdrawing **6e** and donating groups **6d** could be trans-

Keywords: porphyrin-*o*-quinones; electron transfer; *o*-quinones; catecholase; oxidative degradation.

* Corresponding author. Tel.: +49-331-977-5187; fax: +49-331-977-5059; e-mail: mosenge@chem.uni-potsdam.de

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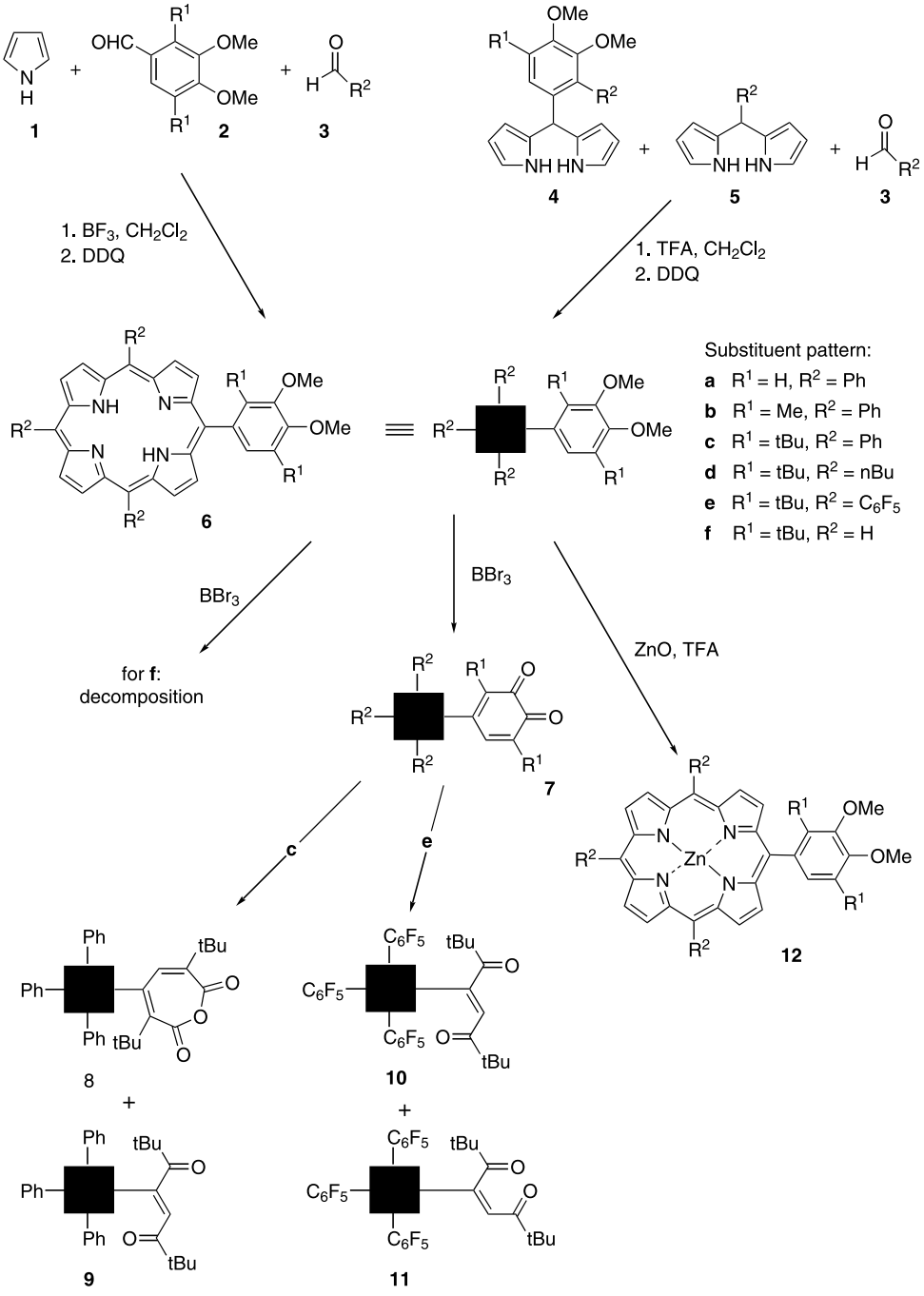
formed into the quinones **7e** and **7d**, respectively. However, while the butyl substituted derivative **7d**[10] proved to be completely stable, formation of the pentafluorophenyl porphyrin **7f** was always accompanied by impurities in 9:1 ratio. NMR and mass spectroscopic data indicated here the additional formation of the two olefinic diketones **10** and **11**. In contrast to **7c** no formation of a muconic acid anhydride (like **8**) was observed. Preparation of the zinc(II) complexes **12c–e** with ZnO and TFA could be accomplished quantitatively and studies on their stability and transformation to the quinones are under way.

Thus, while undergoing intriguing degradation reactions, porphyrin-*o*-quinones with sterically very hindered *o*-quinones tolerate only specific porphyrin substituents which limits their suitability for ET studies, where modulation of the electronic properties of the porphyrin donor via variation of the substituents is a necessary requirement for in-depth studies. Best candi-



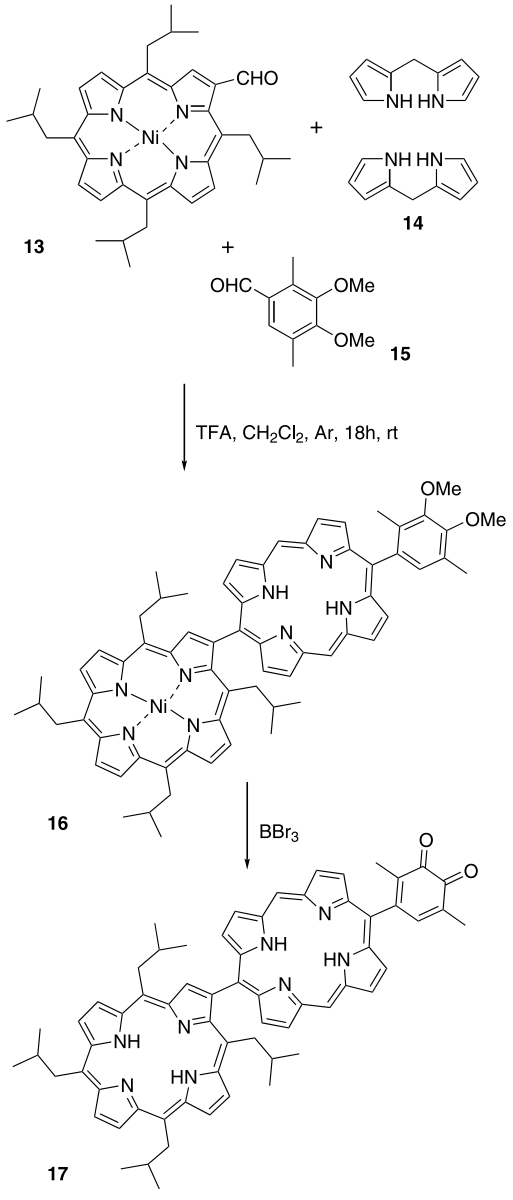
Scheme 1. Synthesis and degradation reactions for various porphyrin-*o*-quinones.

dates for further studies are systems like **7b**, where stabilization of the quinone is achieved by short, unbranched alkyl residues.

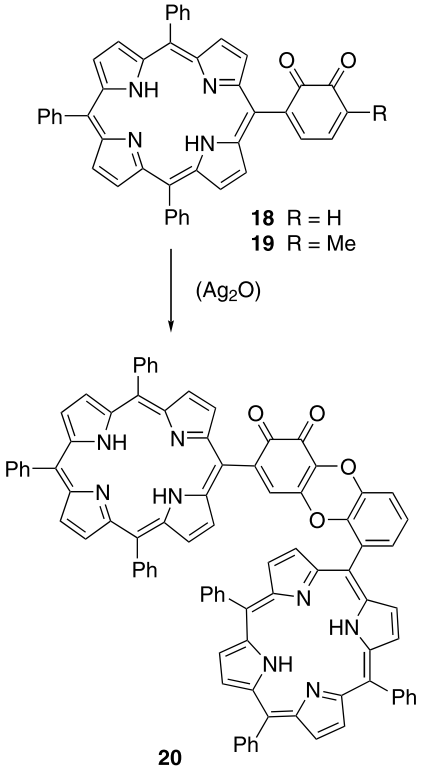
To prove that complex systems containing porphyrin-*o*-quinones can be prepared, we attempted the synthesis of a donor–donor–acceptor triad (Scheme 2). Condensation of the highly soluble formylporphyrin **13**[11] with dipyrromethane **14**[12] and 3,4-dimethoxy-2,5-dimethylbenzaldehyde **15**[5] gave **16** in 8.1% yield. Demethylation and demetalation with BBr_3 at –90°C gave the target porphyrin–porphyrin–*o*-quinone triad **17** in 58% yield as a stable compound.

1,3-Dicarbonyl compounds such as **18** or **19** present additional synthetic possibilities. Compounds with stabilized quinones like **19** constitute an alternative framework for ET model compounds as they are easily prepared via similar methods as described for **7**,[5] can easily be metalated, and do not undergo decomposition reactions. In contrast, compound **18**, prepared by Ag_2O oxidation of the precursor catechol is stable only for a short period of time at 5°C. Within 2 days, quinone **18**, where the triphenylporphyrinyl residue is the sole substituent on the *o*-quinone, undergoes complete decomposition. Repeated treatment of the reaction mixture with Ag_2O increased the yield of one of the decomposition products to 8%, which was identified as the dimer **20** (Scheme 3). Presumably its formation involves partial reformation of the hydroquinol with traces of water, double Michel-type addition to **18**, followed by oxidation to the quinone. Besides 1,3-dipolar cycloadditions,[13] dimerization reactions are typical reactions for *o*-quinones, although not many such reactions have been thoroughly characterized.[14]

Together with the possibility of adjusting the reduction potential of the quinone part via metal chelatization[3] such strategies offer further potential for using porphyrin-based *o*-quinone containing donor–acceptor compounds for ET studies and are the focus of ongoing studies. Alternative strategies might involve the synthesis of porphyrins with electron-rich phenols followed by regioselective oxidation.[15]



Scheme 2. Synthesis of a porphyrin–porphyrin–*o*-quinone triad.



Scheme 3. Dimerization of porphyrin quinone **18**.

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10. *Analytical data for typical compounds*. **7d**: 53%, mp 130°C; ^{1}H NMR (270 MHz, $CDCl_3$): $\delta=9.49$, (4H, *A*B, $^3J=5$ Hz), 9.15 (2H, m), 8.85 (2H, m), 7.43 (1H, s), 4.94 (6H, m), 2.52 (6H, m), 1.84 (6H, m), 1.20 (9H), 0.85 (6H, t, $^3J=7$ Hz), 0.76 (9H, s), −2.55 ppm (2H, s); HRMS $[C_{46}H_{56}N_4O_2]$: calcd 696.44033, found 696.44005; UV/vis (CH_2Cl_2) λ_{max} (lg ε) = 417 (8.23), 520 (6.98), 555 (6.70), 603 (6.64), 661 nm (6.74). **12d**: 90%; mp >330°C; ^{1}H NMR (270 MHz, $CDCl_3$): $\delta=9.46$, (6H, br s), 9.42 (2H, d, $^3J=5$ Hz), 8.79 (2H, d, $^3J=5$ Hz), 7.58 (1H, s), 4.93 (6H, br s), 4.15 (6H, s), 2.54 (6H, br s), 1.86 (6H, br s), 1.39 (9H, s), 1.25 (9H, s), 0.70 ppm (9H, s); HRMS $[C_{48}H_{60}N_4O_2Zn]$: calcd 788.40077, found 788.40013; UV/vis (CH_2Cl_2): λ_{max} (lg *e*) = 422 (5.16), 555 (4.18), 594 nm (3.76). **17**: 56%, mp >320°C, ^{1}H NMR (270 MHz, $CDCl_3$): $\delta=10.35$ (2H, *s*), 10.10 (1H, s), 9.62 (1H, d, $^3J=4.7$ Hz), 9.57 (1H, d, $^3J=4.7$ Hz), 9.53 (2H, s), 9.51 (2H, *d*, $^3J=4.7$ Hz), 9.41 (1H, d, $^3J=4.7$ Hz), 9.38 (2H, d, $^3J=4.5$ Hz), 9.26 (2H, bs), 9.19 (1H, d, $^3J=4.8$ Hz), 9.02 (2H, s), 7.73 (1H, s), 4.96 (2H, d, $^3J=7.2$ Hz), 4.90 (2H, d, $^3J=7.5$ Hz), 4.86 (2H, d, $^3J=7.2$ Hz), 3.60 (2H, d, $^3J=7.2$ Hz), 2.92 (1H, m), 2.81 (2H, m), 2.19 (3H, s), 1.93 (3H, s), 1.87 (1H, m), 1.25 (18H, m), −0.49 (6H, d, $^3J=5.4$ Hz), −2.10 (2H, bs), −2.47, −2.76 ppm (2H, bs); HRMS $[C_{64}H_{64}N_8O_2]$: calcd 976.515224, found 976.51196; UV/vis (CH_2Cl_2) λ_{max} (lg ε) = 433 (5.31), 525 (4.4), 664 nm (3.9). **19**: 8%; mp >330°C; ^{1}H NMR (500 MHz, $CDCl_3$): $\delta=9.06$ (2H, d), 8.95 (4H, d), 8.89 (4H br. s), 8.86 (4H, br s), 8.79 (2H, d), 8.33–8.15 (12H, m), 7.90 (1H, dd), 6.63 (1H, d), 5.68 (1H, s), −2.67 (2H, s), −2.72 ppm (2H, s); MS (FAB): $m/z=1290$, $[C_{88}H_{57}N_8O_4]^{\bullet+}$, $[M+3H]^{\bullet+}$; UV/vis (CH_2Cl_2) λ_{max} (rel. int.) = 417 (1), 412 (0.926 sh), 513 (0.064), 548 (0.022), 589 (0.020), 645 nm (0.012).
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