Corrole Derivatives

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Synthesis of Corrole Derivatives through Regioselective Ir-Catalyzed Direct Borylation**

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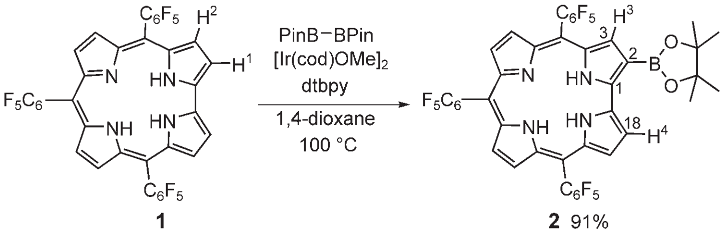
Corroles are 18-π-aromatic tetrapyrrolic macrocycles that contain a direct pyrrole–pyrrole linkage, that exhibit interesting optical properties and unique metal-coordination chemistry, and serve as excellent ligands for oxidation catalysis.[1] Although covalently linked multiporphyrinic molecules have received much attention from the viewpoint of the development of novel functional materials and molecular devices,[2] the synthesis of molecular assemblies based on corroles has remained rather limited owing to the lack of effective synthetic strategies for their regioselective modification.[3] Thus, considerable efforts have been made to develop selective methods that allow the effective functionalization of corroles. However, electrophilic substitution of corroles can occur at the C3 position, and multisubstitution products are sometimes formed.[4] To the best of our knowledge, the selective derivatization of corroles at the C2 position has not been reported. Very recently, we reported the highly regioselective direct borylation of porphyrins at the β position under iridium catalysis.[5,6] Herein, we disclose the successful application of this strategy to 5,10,15-triarylcorroles which enables easy functionalization of the corrole structure at the 2-position with perfect regioselectivity. Owing to the rich chemistry of organoboranes, this strategy offers a powerful tool for the construction of corrole-based molecular assemblies.

A solution of 5,10,15-tris(pentafluorophenyl)corrole (**1**)[7] in dioxane was heated at 100 °C for 24 h with bis(pinacolato)diborane (1.1 equiv) in the presence of a catalytic amount of $[Ir(cod)OMe]_2$ (1.5 mol %) and 4,4′-di-*tert*-butyl-2,2′-bipyridyl (dtbpy; 3.0 mol %) according to the Miyaura–Hartwig–Smith protocol (Scheme 1).[5,6b] Purification by preparative GPC-HPLC afforded the monoborylated corrole **2** in 91 % yield. Introduction of the boryl group was confirmed by the presence of the parent-ion peak at *m*/*z* 921.1529 (calcd for $(C_{43}H_{21}BF_{15}N_4O_2)^-$: 921.1531 ($[M-H]^-$)) by high-resolution electrospray-ionization time-of-flight mass spectrometry (HRMS). Even with the use of excess diborane reagent for a prolonged period, bisborylated corrole could not be obtained. The ^{1}H NMR spectrum of the product revealed its unsymmetrical nature. One singlet and one doublet peak, which can be assigned to hydrogen atoms H^3 and H^4, respectively, were shifted downfield as a result of the neighboring effect of the boryl group which indicates that the boryl group is introduced at the 2-position. This reaction proceeded with perfect regioselectivity, and none of the other isomers were detected.



Scheme 1. Iridium-catalyzed direct borylation of corrole **1**. PinB−BPin = bis(pinacolato)diborane; cod = cycloocta-1,8-diene.

The structure of the 2-boryl-substituted corrole **2** was unambiguously confirmed by X-ray diffraction analysis (Figure 1).[8] The most sterically accessible hydrogen atom H^1 in **1** is replaced by boron. The dioxaborolane rings in **2** are only slightly tilted (27.8°) relative to the corrole core, thereby probably maintaining electronic interaction between the vacant orbital of boron and the π orbital of the core. In this conformation, the bulky tetramethyldioxaborolane moiety hampers the access of a second molecule of the reactive metal complex, hence preventing the second borylation at another pyrrolic site (18-position). While electronic factors generally dominate the regioselectivity at the 3-position in the electrophilic substitution of corroles,[4c–e] the regioselectivity in the present protocol is likely to be determined by steric reasons: the peripheral aromatic groups block borylation at sites other than the 2- and 18-positions. This selectivity is consistent with our observations with previous borylation reactions of porphyrins under iridium catalysis.

Figure 2 shows the UV/Vis absorption and emission spectra of **1** and **2**. The Soret bands as well as the Q bands

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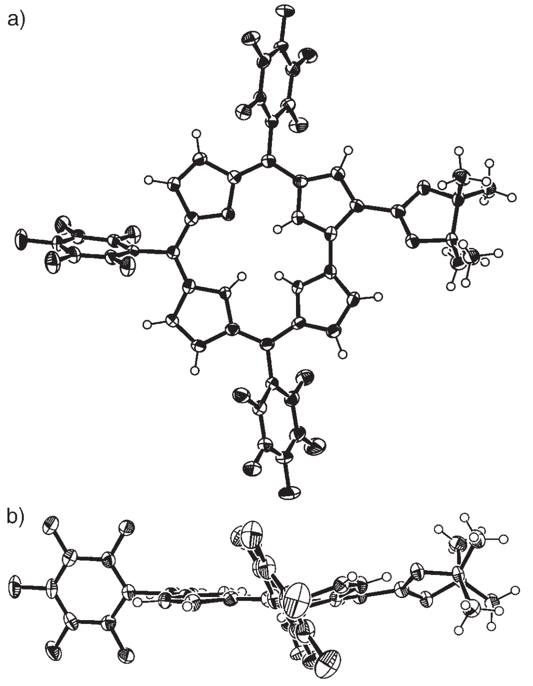
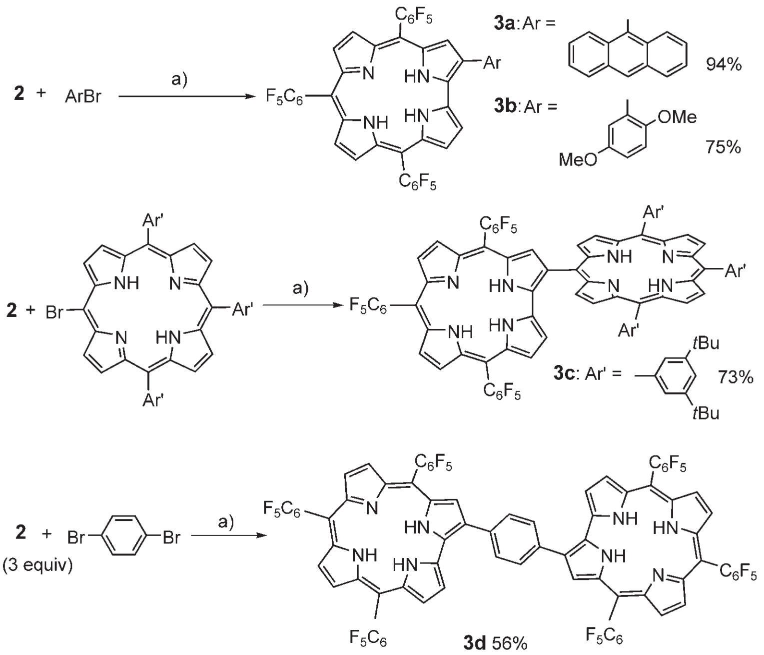


Figure 1. X-ray crystal structure of **2**: a) top view and b) side view.



Scheme 2. Syntheses of 2-functionalized corroles by Suzuki–Miyaura coupling reactions. a) $[(Pd(dba)_2]$, PPh_3, Cs_2CO_3, CsF, toluene/DMF/H_2O. DMF = *N*,*N*-dimethylformamide; dba = dibenzylideneacetone.

of **2** are slightly red-shifted relative to those of **1**. Interestingly, introduction of the boryl group resulted in an increase in the fluorescence intensity.

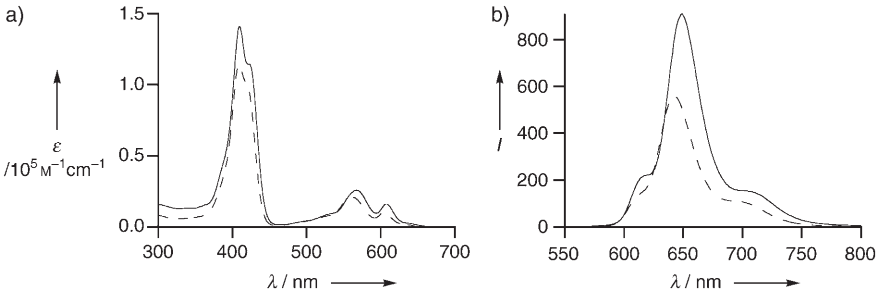
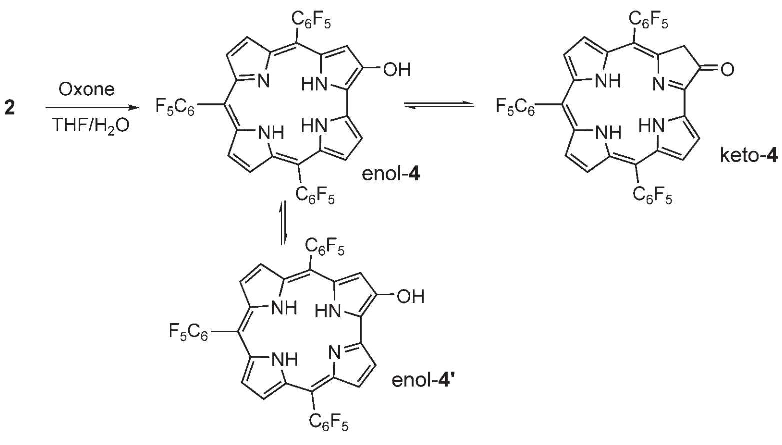


Figure 2. a) UV/Vis absorption spectra and b) emission spectra of **1** (-----) and **2** (——) in CH_2Cl_2.

Organoboron compounds are the most useful substrates for the formation of carbon–carbon bonds by the Suzuki–Miyaura cross-coupling reaction. Indeed, the reaction of **2** with bromoanthracene or bromodimethoxybenzene afforded the desired coupling products **3a** and **3b** in excellent yields (Scheme 2). We also report the synthesis of a directly linked corrole–porphyrin hybrid **3c** through the coupling of **2** with *meso*-bromoporphyrin. In contrast to the recent developments in directly linked porphyrin arrays,[9,10] there has been no previous report on directly linked corrole–porphyrin molecules. Corrole–porphyrin **3c** may be used to ligate two metal ions in different valence states (M^{2+} and M'^{3+}). Additionally, the 1,4-phenylene-bridged dimer **3d** was also very easily obtained by the Suzuki–Miyaura coupling of **2** with 1,4-dibromobenzene. The present procedure provides the desired compounds in excellent yields in only two steps—borylation and cross-coupling—from the original corroles.

The oxidation of organoboranes is a versatile tool for the synthesis of alcohols and phenols. Thus, we attempted the synthesis of 2-hydroxycorroles by oxidation of **2** with oxone according to Smith's procedure (Scheme 3),[11] and oxidation product **4** was obtained in 62% yield. HRMS revealed a parent-ion peak for **4** at *m/z* 811.0629 (calcd for $(C_{37}H_{10}F_{15}N_4O)$: 811.0621 ($[M-H]^-$). The ^{1}H NMR spectrum



Scheme 3. Synthesis of 2-hydroxycorrole and its tautomerization.

of the product in $CDCl_3$ revealed that the keto form, keto-**4**, had been isolated, with the presence of a peak at $\delta = 4.75$ ppm for the two methylene hydrogen atoms (H^a) at the α position of the ketone group. Additionally, signals for the carbonyl and sp^3-hybridized carbon atoms were detected at $\delta = 197.9$ and 45.6 ppm, respectively, in the ^{13}C NMR spectrum of the product in $CDCl_3$. To the best of our knowledge, this is the first reported isolation of the keto form of a dihydrocorrole.[12]

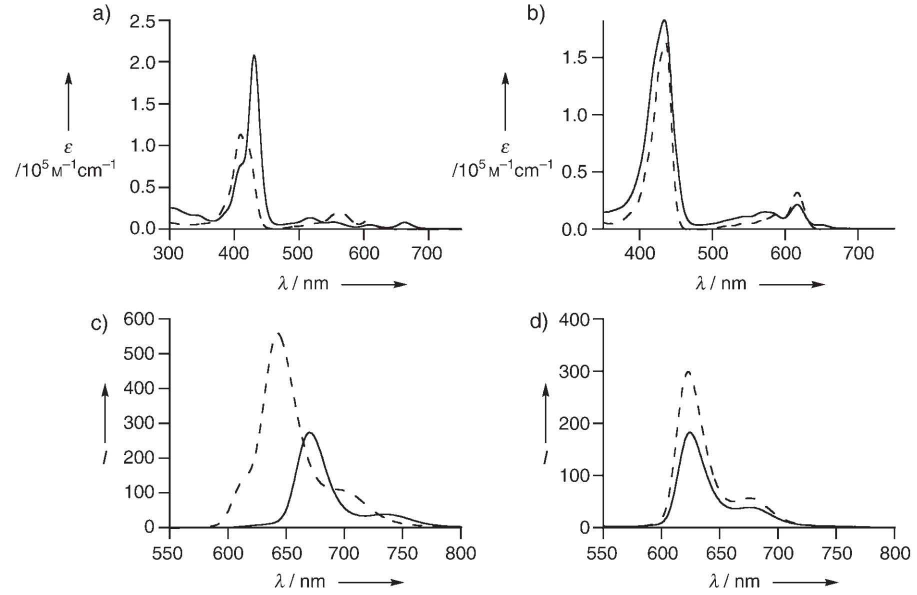


Figure 4. UV/Vis absorption spectra of a) keto-**4** (——) and **1** (-----) in CH_2Cl_2, and b) enol-**4** (——) and **1** (-----) in DMSO. Emission spectra of c) keto-**4** (——) and **1** (-----) in CH_2Cl_2, and d) enol-**4** (——) and **1** (-----), intensity scaled down by 1/10 in DMSO.

In contrast, the enol form enol-**4** was predominant in solution in [D$_6$]DMSO, and the hydroxy proton was detected at $\delta = 11.8$ ppm (Figure 3).[13] While the keto form is exclusively observed in solution in $CDCl_3$ and CD_2Cl_2, both keto and enol structures were detected in varying ratios in [D$_8$]THF, CD_3CN, [D$_6$]acetone, and CD_3OD. Interestingly, the inner NH protons appear as sharp signals at $\delta = -0.44$, -3.05, and -4.84 ppm for the keto form (in $CDCl_3$, while the corresponding signals were very broad at $\delta \approx -0.59$, -1.02, and -3.51 ppm for the enol form (in [D$_6$]DMSO). This observation is consistent with the presence of fixed NH protons in the keto form keto-**4** versus fast NH tautomerism on the NMR timescale between enol forms **4** and **4′** (Scheme 3), as observed for regular corroles.[14] In the enol form, a signal at $\delta = 7.82$ ppm, which was assigned as H^b on the basis of H–H COSY experiments, appeared at higher field than the other β-pyrrolic signals. This shift is caused by the electron-donating nature of the neighboring hydroxy substituent. Interestingly, the signal for H^b gradually decreased upon the addition of D_2O while that for the hydroxy proton disappeared. This result supports the presence of exchange between the OH proton and hydrogen atom H^b through tautomerization.

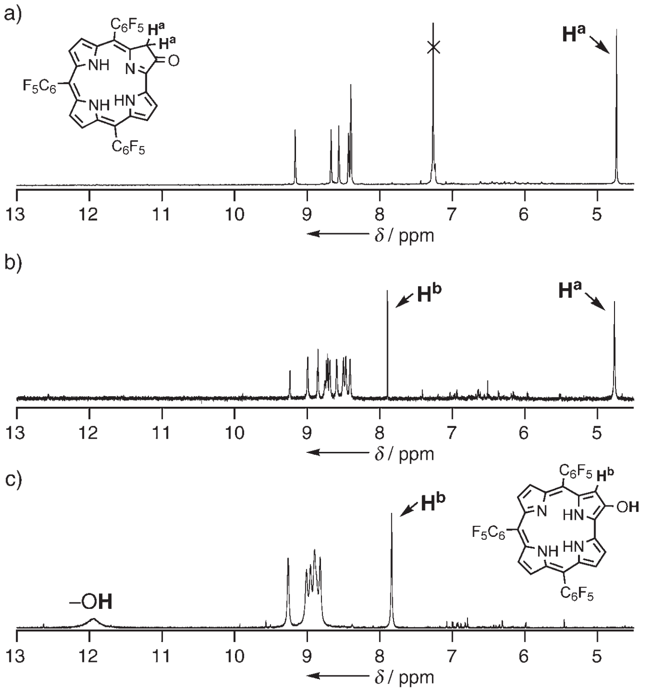


Figure 3. ^1H NMR spectra of **4**: a) keto-**4** in $CDCl_3$, b) keto and enol forms in CD_3CN, and c) enol-**4** in [D$_6$]DMSO (dimethyl sulfoxide).

The UV/Vis and emission spectra of **4** showed a strong dependence on the solvent, reflecting the structural difference between the keto and enol forms (Figure 4). The absorption spectrum of **4** in DMSO is quite similar in shape to that of the original corrole **1** in the same solvent (Figure 4b). In contrast, four Q bands were observed in CH_2Cl_2, probably as a result of the dihydrocorrole structure of the keto form, and the same holds for the red shift of the Soret band (Figure 4a). The enol form emits enol-**4** at the same wavelength as **1**, with a similarly shaped but less-intense spectrum in DMSO (Figure 4d), while the spectrum of the keto form keto-**4** in CH_2Cl_2 was significantly red-shifted relative to that of **1** in the same solvent (Figure 4c). The effect of the hydroxy group in the enol form upon the fluorescence intensity is not clear at this stage.

In conclusion, we have demonstrated the highly regioselective synthesis of a 2-borylated corrole, which is a useful platform for the functionalization of corroles and the construction of molecular assemblies based on corroles. The utility of the present protocol has been demonstrated by the first syntheses of the directly linked corrole–porphyrin hybrid **3c** and the 2-hydroxy-substituted corrole **4**. Further studies involving borylated porphyrins and corroles are currently underway in our laboratory.

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[8] Crystal data for **2**: $C_{43}H_{22}BF_{15}N_4O_2$, $M_W = 922.46$, monoclinic $P2_1/n$ (No. 14), $a = 18.12(7)$, $b = 10.95(5)$, $c = 19.39(10)$ Å, $\beta = 93.74(13)^\circ$, $V = 3838(3)$ Å^3, $T = 123$ K, $\rho_{calcd} = 1.596$ g cm^{-3}, $Z = 4$. For 30529 reflections measured; $R = 0.096$, wR (all data) $= 0.1616$, GOF $= 1.099$ [$I > 2\sigma(I)$]. CCDC-276228 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from the Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

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