Porphyrinoids

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Regioselective Nucleophilic Functionalization of Antiaromatic Nickel(II) Norcorroles**

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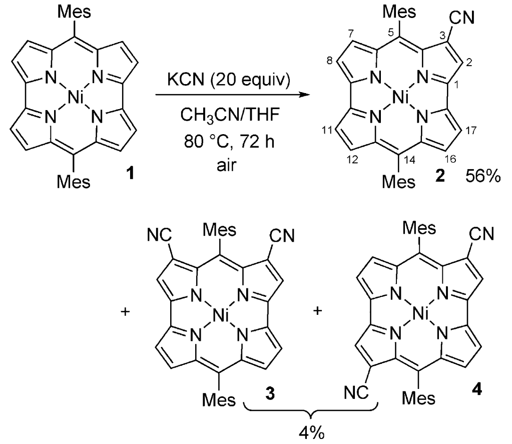
Abstract: *Treatment of antiaromatic nickel(II) norcorrole with potassium cyanide provided nickel(II) 3-cyanonorcorrole with perfect regioselectivity without the help of a catalyst. The reaction of the nickel(II) norcorrole with phenol or thiophenol in the presence of a base also yielded substitution products. The antiaromatic 16π conjugation system in the norcorrole core was preserved in the functionalized products. Introduction of phenylthio groups significantly decreased the HOMO–LUMO gap and enhanced the near IR absorption property.*

Electrophilic substitution is one of the most diagnostic reactions of aromatic compounds. In electrophilic substitution, an electrophile directly replaces hydrogen on an sp^2-carbon atom. In contrast, nucleophilic substitution (S_NAr) is only observed if an aromatic compound possesses both a strong electron-withdrawing group (to activate the substrate) and a halide (to act as a leaving group).[1] Nucleophilic substitution of hydrogen on some electrophilic arenes may also occur through oxidative hydride substitution.[2] The driving force in these processes is aromatic stabilization, which facilitates the formation of the original π-conjugation system in the initial unconjugated addition intermediate.

Antiaromatic compounds are generally unstable and reactive.[3] We recently prepared the antiaromatic nickel(II) dimesitylnorcorrole **1** (see Scheme 1) and explored its properties and functions.[4–6] Herein, we demonstrate that **1** is reactive enough with nucleophiles to furnish substitution products because of its low-lying LUMO. The reaction between **1** and a nucleophile directly afforded either the cyanation or thiolation product regioselectively without the antiaromatic property of the norcorrole core being lost. Although several antiaromatic porphyrinoids have been characterized,[7] this type of nucleophilic substitution reactivity has not been disclosed. The direct C–H cyanation and thiolation of arenes have recently been developed extensively. However, such reactions are only feasible with the help of transition-metal catalysts.[8,9]

Treating **1** with an excess of potassium cyanide (20 equiv) in acetonitrile/THF (1:1) at 80 °C in air afforded the nickel(II) 3-cyanonorcorrole **2** in 56 % yield (Scheme 1). Small amounts of the 3,7- and 3,12-dicyanation products (**3** and **4**, respectively) were also formed in 4 % total yield as a 1:1 regioisomeric mixture. The yield of **1** was dramatically lower when the same reaction was performed under a nitrogen atmosphere, thus indicating that the functionalization reaction proceeds through oxidative hydride substitution.[10] The ^{1}H NMR spectrum of **2** revealed that it was unsymmetrical, with seven pyrrole protons in the upfield region from $\delta = 2.4$ to 3.2 ppm. The anomalous chemical shifts of the pyrrole protons clearly suggest the presence of a strong paratropic ring current in **2**. The calculated nucleus-independent chemical shift (NICS) values were markedly positive (see Table S1 in the Supporting Information), thus confirming the magnetically antiaromatic nature of **2**.[11] Note that the 16π antiaromatic cyclic conjugation network was maintained after cyanation. This result is somewhat counterintuitive because nucleophiles may attack at either the meso- or α-positions to break the antiaromatic π-conjugation circuit.[12] Both dicyanation products **3** and **4** also exhibited upfield-shifted pyrrole protons. The structures of **3** and **4** were assigned on the basis of the identities of the mesityl protons.



Scheme 1. Cyanation of the nickel(II) norcorrole **1** with potassium cyanide. Mes = mesityl, THF = tetrahydrofuran.

We then found that thiophenol could also be regioselectively introduced to **1**. The nickel(II) 3-phenylthionorcorrole **5** was obtained in 29 % yield along with an inseparable mixture of the disubstitution products **6**, **7**, and **8** (12 % yield; see Scheme 2 for structures), when 1.0 equivalent of thiophenol was used in the presence of K_2CO_3 (1.0 equiv) at room

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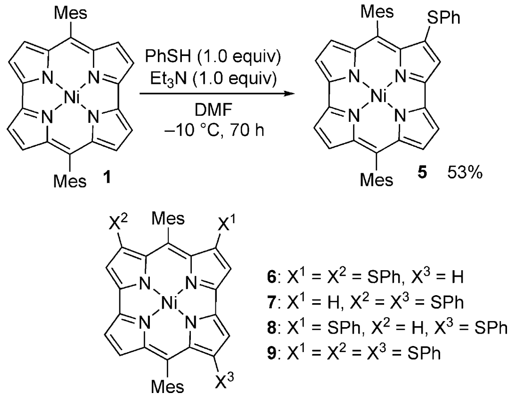
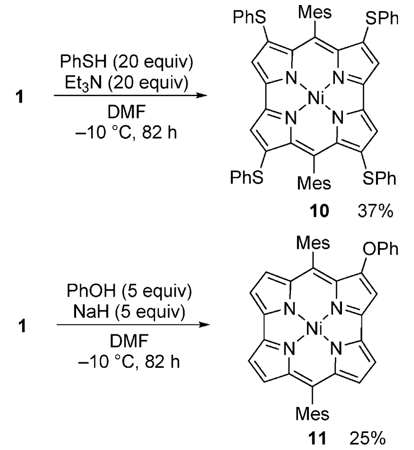


Scheme 2. Substitution of **1** with thiophenol. DMF = *N*,*N*-dimethylformamide.

temperature. The yield of **5** was improved to 53 % with triethylamine (1.0 equiv) as a base at −10 °C (Scheme 2). Unlike with the cyanation reaction, the thiolation of **1** was prone to furnishing multisubstitution products. The use of larger amounts of thiophenol (2.0 equiv) and Et_3N (2.0 equiv) provided **5** and **6**–**8**, as well as the tris(phenylthio)norcorrole **9** in 14, 46, and 9 % yields, respectively. Furthermore, the nickel(II) 3,7,12,16-tetrakis(phenylthio)norcorrole **10** was isolated in 37 % yield in the presence of excess thiophenol (20 equiv) and Et_3N (20 equiv; Scheme 3). The ^{1}H NMR spectra of the thiolated products **5**–**10** also had β-pyrrole protons in the upfield region, from δ = 2.0 to 3.0 ppm, because of the strong paratropic ring-current effect. Sodium phenoxide also underwent the similar nucleophilic substitution reaction with **1** to afford the 3-phenoxynorcorrole **11** in lower yield, but multisubstitution products were not detected in this case.



Scheme 3. Substitution of **1** with thiophenol and phenol.

Single-crystal X-ray diffraction analysis of **2** and **10** allowed the structures of the functionalized norcorroles to be unambiguously elucidated, and the norcorrole core in both was found to retain its planar conformation (Figure 1).[13] The cyanide and thiolate nucleophiles selectively attacked the β-pyrrole positions proximal to the meso-mesityl substituents. This regioselectivity could be explained through DFT calculations. The LUMO of **1** has a substantially larger MO coefficient at the 3-position than at the 2-position, thus resulting in a nucleophilic attack exclusively occurring at the 3-position (see Figure S17). The bond length between S(1) and C(3) is 1.76 Å, which is shorter than that between S(1) and C(25) (1.78 Å; Figure 1 c). This distance indicates that the lone pair on sulfur is more effectively conjugated to the norcorrole core than the phenyl ring.

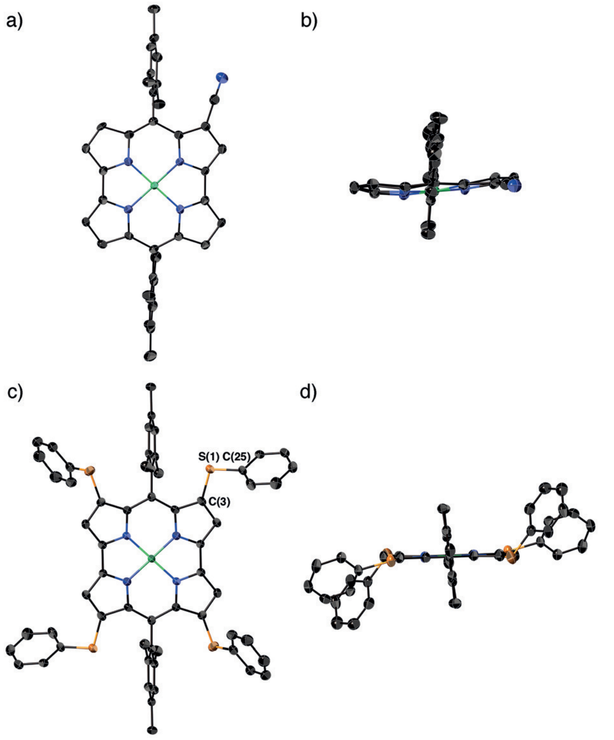


Figure 1. Crystal structures of **2** and **10**. a) Top and b) side views of **2**. c) Top and d) side views of **10**. Protons are omitted. The thermal ellipsoids were calculated at the 50 % probability level.

The electrochemical properties of **1**, **2**, **5**, and **10** were investigated using cyclic voltammetry (see Table 1 and Figure S15) to gain insight into the electronic effects of the substituents. All the norcorrole complexes exhibited two reversible reduction waves and two reversible oxidation waves, thus indicating the stabilities of these molecules to redox reactions. The cyano group induced anodic shifts in both the reduction and oxidation potentials, whereas intro-

Table 1: Summary of the electrochemical data.[a]

Compound	E_{ox2}	E_{ox1}	E_{red1}	E_{red2}	$\Delta E^{[b]}$
1	0.789	0.162	−0.920	−1.700	1.082
2	0.915	0.371	−0.676	−1.290	1.047
5	0.682	0.102	−0.823	−1.559	0.925
10	0.530	0.0535	−0.815	−1.347	0.869

[a] Solvent: CH_2Cl_2, electrolyte: Bu_4NPF_6, working electrode: glassy carbon, counter electrode: Pt, reference electrode: $Ag/AgClO_4$, scan rate: 0.1 $V s^{-1}$. The potentials versus the value for the ferrocene/ferrocenium cation couple are shown. [b] $\Delta E = E_{ox1} - E_{red1}$.

ducing phenylthio substituents resulted in cathodic shifts only in the oxidation potentials. The first oxidation and first reduction potentials were found to be higher for **2** (E_{ox1} = 0.371 V and E_{red1} = −0.676 V) than for **1** (E_{ox1} = 0.162 V and E_{red1} = −0.920 V). However, the first oxidation potentials were significantly lower for **5** and **10** (E_{ox1} = 0.102 V and 0.0535 V, respectively), and the reduction potentials for **5** and **10** were shifted to E_{red1} = −0.823 V and −0.815 V, respectively. Accordingly, the electrochemical HOMO–LUMO gaps (ΔE) of **5** (0.925 V) and **10** (0.869 V) were substantially smaller than those of **1** (1.082 V) and **2** (1.047 V).[14] This change can be explained by donation of the lone pair on sulfur to the macrocycle to destabilize the HOMO level. These results demonstrate that the electrochemical properties of norcorroles could be tuned effectively by the peripheral functionalization.

Figure 2 shows the UV/Vis/NIR absorption spectra of the norcorroles **1**–**10** in dichloromethane. Cyanation resulted in attenuation of the sharp absorption band for **1** at λ = 430 nm and appearance of broad absorption bands from λ = 600 to 1100 nm especially in the case of dicyanonorcorroles (Figure 2a). Introducing phenylthio groups also caused new absorption bands around λ = 500 and 1000 nm (Figure 2b). Interestingly, polysubstituted norcorroles exhibited broad NIR absorption bands, while the spectra of monosubstituted norcorroles are similar to that of **1**. We performed theoretical calculations to clarify the origins of these absorption characteristics. TD-DFT calculations suggested that the new NIR absorption bands of functionalized norcorroles originated in HOMO-1→LUMO and HOMO-2→LUMO transitions (see Figure S16 and S17). These frontier orbitals were found to have substantial contributions from sulfur of phenylthio groups and nitrogen of cyano groups (see Figure S18). The low-energy absorption bands of antiaromatic compounds are usually very weak because of their forbidden nature. However, the significant changes found in the absorption of substituted norcorroles demonstrated the possibility of tuning the absorption features of antiaromatic compounds using the substituent effect.

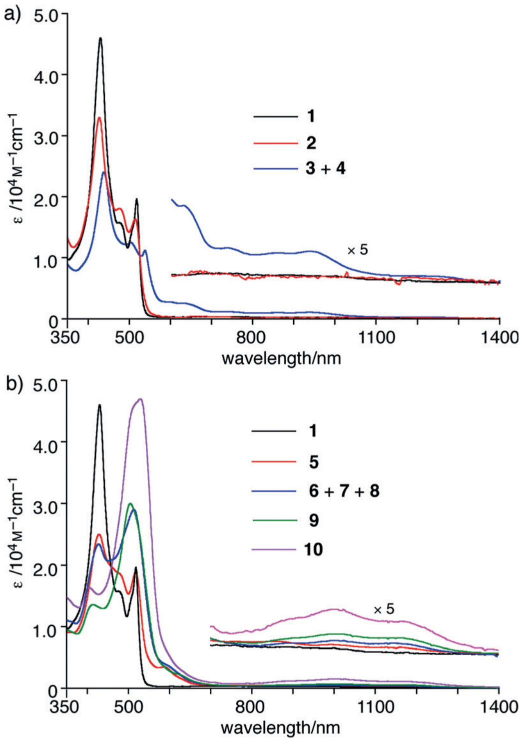


Figure 2. UV/Vis/NIR absorption spectra of **1** and the cyanonorcorroles **2**–**4** (a), and **1** and the phenylthionorcorroles **5**–**10** (b) in dichloromethane.

In conclusion, we achieved a facile nucleophilic peripheral functionalization of a nickel(II) norcorrole. The pyrrole protons adjacent to the meso substituents were replaced with cyano, phenylthio, or phenoxy groups with excellent regioselectivity. Interestingly, the antiaromatic 16π conjugation system was preserved after the nucleophilic addition had occurred. The present protocol would enable creation of low-band-gap materials through fine-tuning of the electrochemical properties of nickel(II) norcorroles. We are currently investigating the preparation and properties of other functionalized norcorroles.

Keywords: aromaticity · electrophilic substitution · nickel · porphyrinoids · X-ray diffraction

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[10] Although the detailed mechanism is not clear at this moment, we speculate that the reaction involves nucleophilic addition to **1** followed by air-oxidation of the intermediate.

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[12] The addition of butyllithium to **1** at −78 °C provided the α-addition product in 29 % yield.

[13] Crystallographic data for **2**: $C_{37}H_{29}N_5Ni$, $M_w = 602.36$, monoclinic, $P2_1/n$, $a = 8.7336(4)$, $b = 12.7797(7)$, $c = 26.1810(13)$ Å, $\beta = 98.8780(13)^\circ$, $Z = 4$, $R = 0.0375$ ($I > 2.0\sigma(I)$), $R_w = 0.1037$ (all data), GOF = 1.120. Crystallographic data for **10**: $C_{60}H_{46}N_4NiS_4$, $M_w = 1009.96$, monoclinic, $P2_1/n$, $a = 12.710(3)$, $b = 11.290(3)$, $c = 17.030(5)$ Å, $\beta = 104.060(4)^\circ$, $Z = 2$, $R = 0.0643$ ($I > 2.0\sigma(I)$), $R_w = 0.1746$ (all data), GOF = 1.107. CCDC 1054678, 1054679 contain 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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