π-Conjugated Systems

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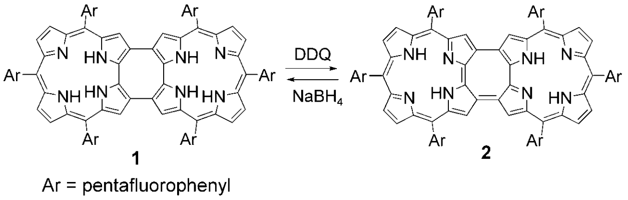
Zwitterionic Corroles: Regioselective Nucleophilic Pyridination of a Doubly Linked Biscorrole**

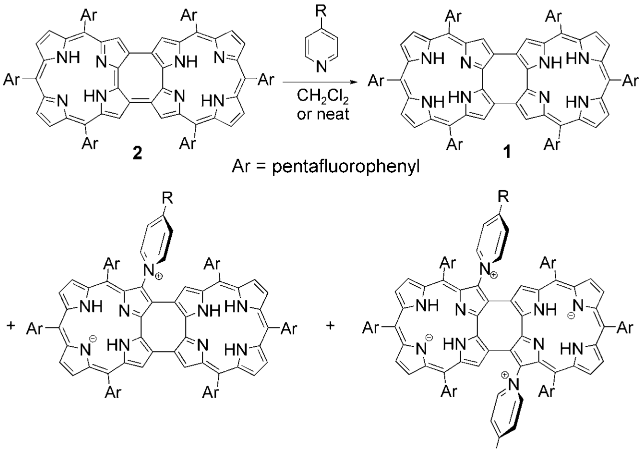
Satoru Hiroto, Naoki Aratani, Naoki Shibata, Yoshiki Higuchi, Takahiro Sasamori, Norihiro Tokitoh, Hiroshi Shinokubo, and Atsuhiro Osuka**

Extensively π-conjugated systems have attracted considerable attention because of their possible applications in the area of functional materials. We have recently synthesized doubly linked biscorrole **1**, which is easily oxidized to **2** (Scheme 1). The oxidized biscorrole **2** exists as a stable singlet biradical species in the ground state.[1] We then set out to explore the chemical reactivity of this unique biradical biscorrole **2**. Owing to the strongly electron-deficient nature of **2**, further functionalization of **2** should be possible by direct nucleophilic addition reactions. Although several electrophilic substitution reactions with modest regioselectivities have been reported so far, no nucleophilic addition reactions to neutral corroles have been reported to date.[2–4] We report herein a highly regioselective nucleophilic addition reaction to **2** that occurs exclusively at the 3 and 3′ positions in the bay area to produce stable zwitterions (Scheme 2). Furthermore, the zwitterionic biscorroles have unique photophysical properties and selective sensing ability for the fluoride ion.



Scheme 1. Redox interconversion between doubly linked biscorroles. DDQ = 2,3-dichloro-5,6-dicyano-1,4-benzoquinone.

Upon treatment of **2** with pyridine, the color of the solution gradually changed from green to brown. After stirring at room temperature for 14 hours, the starting material **2** completely disappeared to yield three products. These products were easily separated by column chromatography on silica gel. The first fraction was reduced biscorrole **1** (22 % yield), the second fraction was the pyridine addition product **3a** (60 % yield), the mass spectrum of which exhibited the parent ion peak at *m*/*z* 1664.1350 (calcd for $(C_{79}H_{20}F_{30}N_9)^- = 1664.1368$ $[(M-H)^-]$). The ^{1}H NMR spectrum of **3a** displays signals that correspond to the five protons of the pyridyl substituent in a 2:1:2 (*ortho*/*para*/*meta*) ratio, which indicates its attachment at the nitrogen atom. Four pairs of mutually coupled doublet signals for the β-pyrrolic protons and three proton singlets were also observed. This indicates that the addition occurred selectively at the most sterically congested β positions, namely the bay area, of biscorrole **2**. It is noteworthy that two NH protons appeared at $\delta = 4.57$ and 3.42 ppm along with broad signal of NH protons around $\delta = -3$ ppm, where NH protons of ordinary corroles appear.[5] Such low-field shifts of NH protons can be accounted for by the existence of hydrogen-bonding interactions in one of the corrole rings. The third fraction was shown by its parent mass ion peak at $m/z = 1743.1810$ in the mass spectrum (calcd for $(C_{84}H_{25}F_{30}N_{10})^+ = 1743.1779$ $[(M)^+]$)



3a: R = H (61%)
3b: R = OMe (24%)
3c: R = NMe$_2$ (24%)

4a: R = H (9%)
4b: R = OMe (5%)
4c: R = NMe$_2$ (10%)

Scheme 2. Nucleophilic pyridination of **2** with *para*-substituted pyridines.

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[*] S. Hiroto, Prof. Dr. H. Shinokubo
Department of Applied Chemistry
Graduate School of Engineering, Nagoya University
Nagoya 464-8603 (Japan)
Fax: (+81) 52-789-5113
E-mail: hshino@apchem.nagoya-u.ac.jp

Dr. N. Aratani, Prof. Dr. A. Osuka
Department of Chemistry, Graduate School of Science
Kyoto University, Kyoto 606-8502 (Japan)
Fax: (+81) 75-753-3970
E-mail: osuka@kuchem.kyoto-u.ac.jp

Dr. T. Sasamori, Prof. Dr. N. Tokitoh
Institute for Chemical Research, Kyoto University
Kyoto 611-0011 (Japan)

Prof. Dr. N. Shibata, Prof. Dr. Y. Higuchi
Graduate School of Life Science, University of Hyogo
Hyogo 678-1297 (Japan)
and
The RIKEN Spring-8 Center, Hyogo 678-5248 (Japan)

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to be the double addition product **4a** (5% yield). The ^{1}H NMR spectrum of **4a** showed it to have a C_2-symmetric structure with two pyridine substituents at the bay area. Furthermore, the *anti* relationship of two pyridyl substituents was elucidated from the ^{19}F NMR spectrum, which showed only three kinds of signals for the *ortho*, *meta*, and *para* fluorine atoms. The molecule **4a** has two NH protons in each of corrole rings, which give rise to two signals for the NH protons at $\delta = 3.70$ and 2.63 ppm.

Importantly, this reaction is specific to the biradical species **2**, no reaction occurred with **1** under the same conditions. The reaction was also performed with various *para*-substituted pyridine derivatives. Pyridines with electron-donating substituents such as methoxy and dimethylamino groups furnished mono and double addition products in moderate to good yields. In contrast, no reaction of 4-cyanopyridine with **2** occurred even at elevated temperatures, which indicated the nucleophilic nature of this addition process.

The X-ray crystal structure of **4a** is shown in Figure 1.[6] Each corrole ring has two NH protons and hydrogen-bonding interactions appear to exist between N(2)H and N(3), and N(4)H and N(3), since the distances for N(2)–N(3) and N(4)–N(3) are 2.63 and 2.91 Å, respectively. The structure of **4a** is distorted and the mean plane deviation of **4a** defined by the constitutional 46 atoms is substantial (0.687 Å). The distortion is presumably caused by the steric repulsion between the pyridine substituents and the adjacent β protons. Intriguingly, two molecules of **4a** are closely assembled, as shown in the crystal packing (Figure 1b). Cationic pyridinium substituents are located just above the anionic corrole rings, which suggests a Coulombic interaction between two aggregated molecules. In addition, quadruple hydrogen-bonding interactions operate between the two corrole molecules: the distance between the *ortho* carbon atom of the pyridyl group and inner nitrogen atom of the adjacent corrole molecule is 3.34 Å (averaged over four values). Such aggregation behavior of **4a** is also observed in solution (temperature-dependent ^{1}H NMR spectra of **4a** (1.1×10^{-3} M in [D$_8$]toluene) are shown in Figure S10 in the Supporting Information). Upon increasing the temperature, low-field shifts for the pyridinium protons and the β-pyrrolic protons at the bay area were observed, while other β protons were shifted upfield. The directions of the shift of each signal are explained by the dissociation of the dimer at higher temperatures.

To investigate the origin of the regioselectivity of this reaction, a DFT calculation of **1** was performed (see Figure S20 in the Supporting Information for two singly occupied molecular orbitals (SOMOs) of **1** calculated at the UB3LYP/6-31G(d) level with the broken-symmetry (BS) method[7]). The present regioselectivity is clearly explained by the larger MO coefficient at the C(3) position being larger than those at the other β-carbon atoms of the SOMO.

Figure 2a shows UV/Vis absorption spectra of **1**, **3a**, and **4a** recorded in dichloromethane. The electronic absorption spectrum of **1** exhibits a characteristic S_0–S_1 band with a large extinction coefficient at 722 nm. In the cases of **3a** and **4a**, the S_0–S_1 bands become broader with concomitant bathochromic shifts from 722 nm to 791 nm. Furthermore, these absorption bands of **4a** exhibit a negative solvatochromic effect (see Figure S11 in the Supporting Information), namely blue shifts of the lowest energy Q-like bands with an increase in solvent polarity. This behavior is characteristic of zwitterionic species that have a large dipole moment in the ground state and a smaller dipole moment in the excited state. Consistent with this interpretation, a plot of normalized $\lambda_{\max}$ of **4a** in various solvents versus the $E_T(30)$ parameter shows a linear correlation for moderately polar solvents (see Figure S12 in the Supporting Information).[8] Figure 2b shows the fluorescence spectra of **1**, **4a**, **4b**, and **4c** in CH_2Cl_2. While **4b** fluoresces at 800 nm, the fluorescence of **4a** is completely quenched in CH_2Cl_2, which suggests charge transfer from the anionic corrole to the pyridinium moieties. The appearance of fluorescence from **4b** and **4c** is explained by the suppressed electron-accepting ability of the pyridinium moieties that arises from the strongly electron-donating *para*-methoxy and amino groups.[9] The fluorescence intensity clearly correlates with the electronic properties of the pyridyl group.

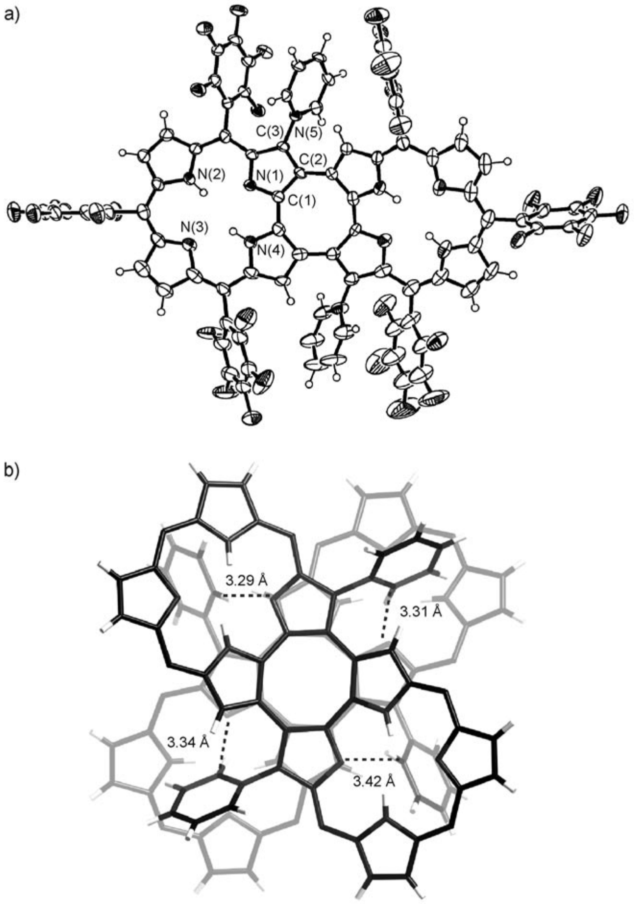

Figure 1. X-ray crystal structure of **4a**. a) Top view and b) the crystal packing structure. Thermal ellipsoids are at the 50% probability level. Pentafluorophenyl substituents are omitted for clarity in the side view.

Such efficient intramolecular fluorescence quenching of **4a** in the solution state has been applied to anion sensing.[10] Upon addition of tetrabutylammonium fluoride (TBAF) to a solution of **4a** in CH_2Cl_2, the lowest-energy absorption band of **4a** is blue-shifted and attenuated because of the gradual interruption of the charge-transfer process (Figure 3). The addition of chloride or dihydrogenphosphate ions did not

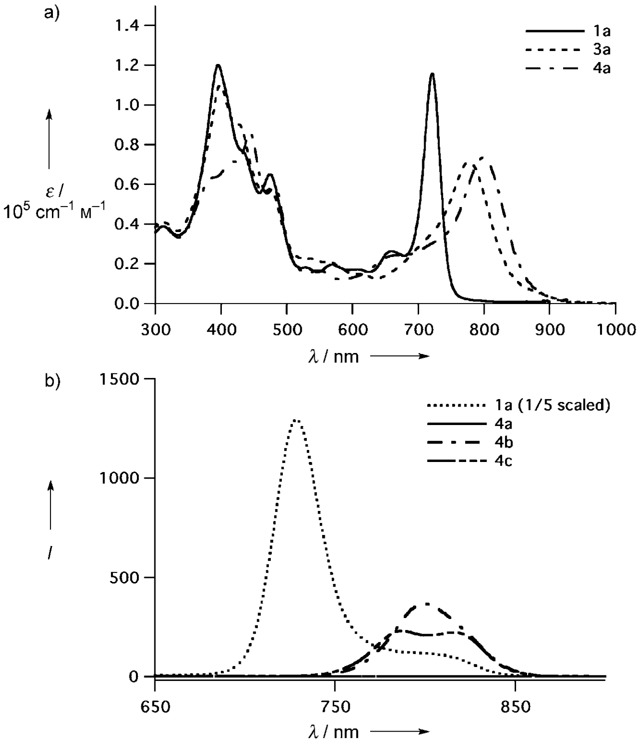

Figure 2. a) UV/Vis spectra of **1** (——), **3a** (-----), and **4a** (–•–•) in CH_2Cl_2. b) Fluorescence spectra of **1** (•••••), **4a** (——), **4b** (–•–•), and **4c** (–••–••) recorded in CH_2Cl_2 with excitation at 610 nm.

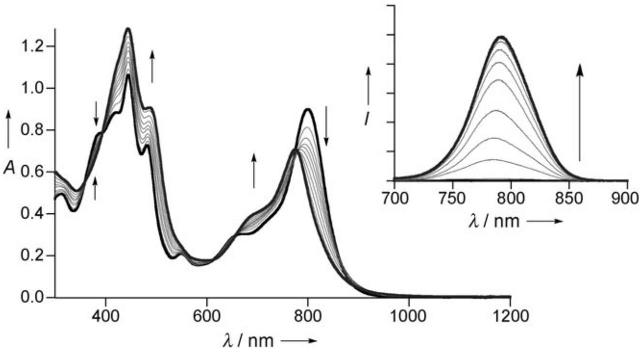

Figure 3. UV/Vis absorption and fluorescence (inset) spectra of **4a** (12 μM) upon titration with TBAF (0–500 μM) in CH_2Cl_2.

induce any changes. The addition of triethylamine as a base also resulted in no changes, thus excluding the role of fluoride ions as a base. Association constants of $K_1 = 4300\,\mathrm{M}^{-1}$ and $K_2 = 2800\,\mathrm{M}^{-1}$ were obtained for fluoride ion binding by using a ^{1}H NMR titration with the least-squares method assuming 1:2 binding.[11] The addition of fluoride ions also caused a dramatic enhancement in the fluorescence intensity of **4a**. The fluoride ion binding was supported by spectroscopic studies. The high-resolution cryospray ionization mass spectrum (CSI-TOF-MS) of **4a** in the presence of TBAF shows a peak at m/z 1761.1661, which agrees with the calculated value of m/z 1761.1696 $[(\mathbf{4a}+\mathrm{F})^-]$. The ^{1}H NMR titration study showed large upfield shifts and desymmetrization of the pyridinium signals, which probably arise from the proximity of a fluoride ion to the pyridinium substituent. A preliminary X-ray analysis indicated the existence of unassignable electron densities, which could arise from disordered fluoride ions near the pyridinium moiety (see Figure S17 in the Supporting Information). On the basis of these results, we conclude that a fluoride ion is located close to the pyridinium moiety and weakens its electron-accepting nature.[12]

In summary, we have achieved regioselective functionalization of a doubly linked biscorrole by a unique nucleophilic addition to singlet biradical species. The products are stable zwitterionic species that show a negative solvatochromic effect. Furthermore, intermolecular charge transfer between the anionic corrole and the pyridinium cation can be applied to selective recognition of a fluoride anion. Further investigations on the chemistry of doubly linked biscorroles are under way.

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[6] $C_{100}H_{40}F_{30}N_{10}$, $M_r = 1855.16$, triclinic, space group $P\bar{1}$ (no. 2), $a = 18.797(4)$, $b = 21.461(4)$, $c = 23.365(5)$ Å, $\alpha = 110.577(4)$, $\beta = 91.006(4)$, $\gamma = 111.361(3)°$, $V = 8103(3)$ Å^3, $Z = 4$, $T = 90(2)$, $\rho_{\mathrm{calcd}} = 1.595\,\mathrm{g\,cm^{-1}}$, $R_1 = 0.0944$ $(I > 2\sigma(I))$, $wR_2 = 0.3038$ (all data), GOF = 1.007. CCDC 710218 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.
[7] The keyword "Guess = mix" was used for the DFT calculation to obtain the solution for a singlet biradical state.
[8] The data obtained in nonpolar solvents do not show such a good linear correlation probably because of solvent effects.
[9] Lippert–Mataga plots of **4a**, **4b**, and **4c** (Figure S13) also indicate the decreased charge-transfer character of **4b** and **4c**. In addition, DFT calculations (see Figure S21 in the Supporting Information) support this conclusion.
[10] For anion binding studies with porphyrin derivatives, see; a) J. L. Sessler, J. M. Davis, *Acc. Chem. Res.* **2001**, *34*, 989; b) J. L. Sessler, S. Camiolo, P. A. Gale, *Coord. Chem. Rev.* **2003**, *240*, 17.
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