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Synthesis of *meso*-Azulenylporphyrins

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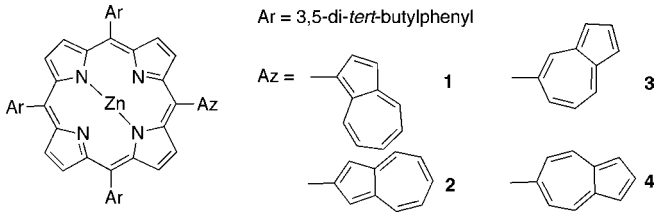
ABSTRACT



***meso*-Azulenylporphyrins 1–4 were prepared by Suzuki–Miyaura coupling or the Ziegler–Hafner method. 1-Azulenyl and 6-azulenyl groups are indeed acting as electron-donating and electron-accepting substituents toward Zn(II) porphyrin. Fluorescence of Zn(II) porphyrin in the dyads is strongly quenched depending upon substitution position of azulene in order of 2 > 1 > 4 > 3.**

Azulene is a nonalternant aromatic hydrocarbon featuring quite unique characteristics of blue color and a permanent dipole moment of ca. 1 D. In recent years, considerable efforts have been made toward exploration of a variety of functional dyes and nonlinear optical materials based on this unique π-system.[1] On the other hand, azulene can serve as either an electron donor or an electron acceptor depending on the nature and connectivity of the substituent, as judged from the well-known electron-rich nature of the five-membered ring and the electron-deficient nature of the seven-membered ring. In the course of our own project to pursue novel functional porphyrinoid molecules, we anticipated that the covalent attachment of azulene to porphyrin would provide a substantial impact to porphyrin chromophores. Despite high potential and unique characteristics of azulenes, to the best of our knowledge, there is no example of a covalently linked azulenylporphyrin,[2] while several azuliporphyrins have been developed by incorporating an azulene moiety into porphyrin or core-modified porphyrin macrocycles.[3] One of the objectives in the present study is to examine the possibility that the substituent effects of azulenyl moiety can be modulated to be either electron-donating or electron-accepting, depending upon the substitution position of the azulene.

Initially, we attempted the synthesis of azulenylporphyrins via acid-catalyzed condensation of 1-formylazulene, 1-formyl-3-methoxycarbonylazulene, 1,3-dichloro-2-formylazulene, or 1,3-dichloro-6-formylazulene with 3,5-di-*tert*-butylbenzaldehyde and pyrrole under Adler and Lindsey conditions.[4] We also attempted the condensation reaction of *meso*-azulenyl dipyrromethane with aromatic aldehyde under similar conditions. However, all of these attempts failed to provide azulenylporphyrins. In some cases, the MALDI-TOF analysis of the reaction mixture revealed the formation of desired porphyrinogen intermediates, which however disappeared without providing porphyrin products upon oxidation with DDQ or *p*-chloranil. Particularly, 1-formylazulene

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(2) After the submission of this paper, one of the reviewers informed us of a paper that reported covalently linked azulene-porphyrin. Yeow, E. K. L.; Ziolek, M.; Karolczak, J.; Shevyakov, S. V.; Asato, A. E.; Maciejewski, A.; Steer, R. P. *J. Phys. Chem. A* **2004**, *108*, 10980.

(3) (a) Lash, T. D.; Chaney, S. T. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 839. (b) Graham, S. R.; Colby, D. A.; Lash, T. D. *Angew. Chem., Int. Ed.* **2002**, *41*, 1371. (c) Colby, D. A.; Ferrence, G. M.; Lash, T. D. *Angew. Chem., Int. Ed.* **2004**, *43*, 1346. (d) Venkatraman, S.; Anand, V. G.; PrabhuRaja, V.; Rath, H.; Sankar, J.; Chandrashekar, T. K.; Teng, W.; Senge, K. R. *Chem. Commun.* **2002**, 1660.

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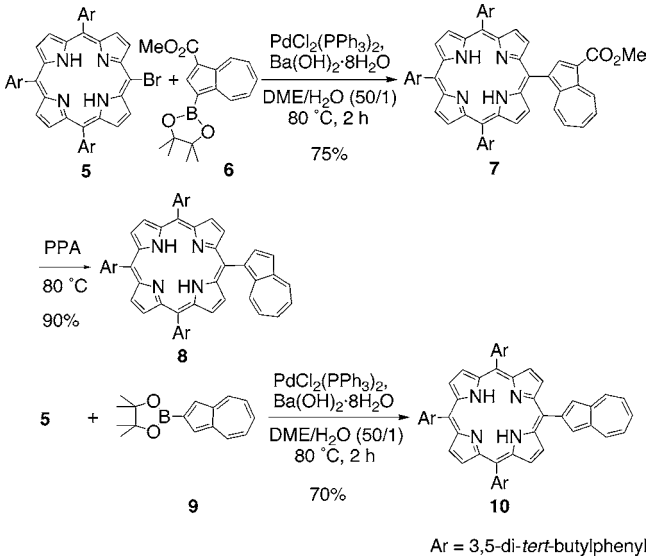
effectively underwent unwanted decarbonylation upon treatment with acid in the presence of pyrrole, as reported by others.[5]

We prepared 5-(3-methoxycarbonyl-1-azulenyl)-10,15,20-triarylporphyrin **7** by Suzuki−Miyaura coupling of *meso*-bromoporphyrin **5** (Supporting Information) with 2-(3-methoxycarbonyl-1-azulenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane[6] (**6**) (Scheme 1). After examining various

Scheme 1



reaction conditions, we found that a combination of $PdCl_2(PPh_3)_2$ and $Ba(OH)_2{\cdot}8H_2O$ in DME and water[7] was most effective to afford **7** in 75% yield, which was subsequently decarboxylated with polyphosphoric acid (PPA) at 80 °C to give **8**. 5-(2-Azulenyl)-10,15,20-triarylporphyrin **10** was prepared in a similar manner from **5** and 2-(2-azulenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane[8] (**9**) in 70% yield. Both azulenylporphyrins **8** and **10** were metalated with $Zn(OAc)_2$ to give **1** and **2** quantitatively. The dyads **1** and **2** have been characterized by ^{1}H NMR, ^{13}C NMR, and FAB mass spectra (Supporting Information). In the ^{1}H NMR spectra, the H^2- and H^3-protons of **1** appear as a pair of doublets (J = 3.7 Hz) at 8.80 and 7.85 ppm, while the H^1- and H^3-protons of **2** appear as a singlet at 8.37 ppm. The structure of **2** has been confirmed by its X-ray crystal structural analysis (Figure 1).[9] The 2-azulenyl substituent is linked to the porphyrin ring with a C−C bond length of 1.47

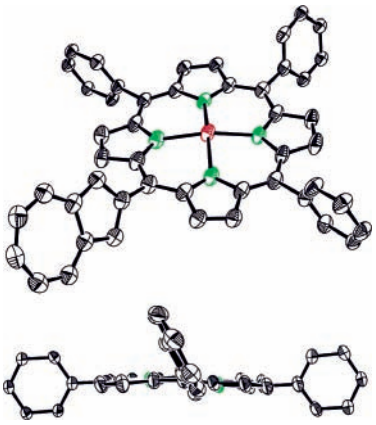


Figure 1. X-ray crystal structure of **2**. 3,5-Di-*tert*-butyl groups and hydrogen atoms are omitted for clarity.

Å and a dihedral angle of 58°. Other C(meso)−C(aryl-ipso) bond lengths are 1.50, 1.49, and 1.51 Å, and dihedral angles are 79°, 59°, and 80° for 10-, 15-, and 20-aryl substituents, respectively.

On the other hand, azulenylporphyrins linked at the seven-membered ring were prepared by a different synthetic route, since the preparation of a requisite 6-azulenylboronic ester[4,10] needs many steps and 4- and 5-azulenylboronic esters are unknown compounds. We employed the strategy developed by Ziegler and Hafner, in which an activated pyridinium moiety is cleaved by nucleophilic reaction with amine and the resulting iminium salt is condensed with sodium cyclopentadienide.[11] This method is useful for the synthesis of azulene substituted at its seven-membered ring.[12]

Thus, *meso*-pyridyl-substituted porphyrins **11**[13] and **12** (Supporting Information) were prepared through cross condensation porphyrin synthesis under Adler conditions[3a] and were subjected to the Ziegler−Hafner method.[10] Our first attempt using 1-chloro-2,4-dinitrobenzene as an activator of pyridine moiety was unsuccessful, probably due to low basicity of the pyridine moiety in **11**. This seems to arise from a strongly electron-withdrawing nature of the linked porphyrin. After considerable experimentation, we found trifluoromethane-sulfonic anhydride (Tf_2O) to be an efficient activator of the pyridine moiety in **11**. The 3-pyridyl-substituted porphyrin **11** was treated with Tf_2O for 5 min at 0 °C and the resulting mixture was reacted with diethylamine and sodium cyclopentadienide under reflux for 10 h. After the usual workup, separation over a silica gel column gave 5-(5-azulenyl)-10,15,20-triarylporphyrin **13** in 15% yield. When this reaction was applied to *meso*-(4-pyridyl)porphyrin

(5) Ito, S.; Morita, N.; Asao, T. *Bull. Chem. Soc. Jpn.* **1999**, *72*, 2543.
(6) Kurotobi, K.; Tabata, H.; Miyauchi, M.; Murafuji, T.; Sugihara, Y. *Synthesis* **2002**, 1013.
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(8) Kurotobi, K.; Miyauchi, M.; Takakura, K.; Murafuji, T.; Sugihara, Y. *Eur. J. Org. Chem.* **2003**, 3663.
(9) Crystal data of **2**: $C_{72}H_{78}N_4Zn{\cdot}3(C_3H_7OH)$ = 1245.10, triclinic, space group P-1, a = 10.647(4), b = 19.322(9), c = 19.856(9) Å, α = 118.47(3)°, β = 95.91(4)°, γ = 97.29(4)°, V = 3498 Å^3, Z = 2, D_{calcd} = 1.182 g cm^{-3}, T = 123 K, crystal size 0.50 × 0.45 × 0.25 mm^3, R = 0.084, Rw = 0.121, GOF = 1.369.
(10) Ito, S.; Kubo, T.; Morita, N.; Matsui, Y.; Watanabe, T.; Ohta, A.; Fujimori, K.; Murafuji, T.; Sugihara, Y.; Tajiri, A. *Tetrahedron. Lett.* **2004**, *45*, 2891.
(11) Hafner, K. *Organic Syntheses*; Wiley: New York, 1990; Collect. Vol. VII, p 15.
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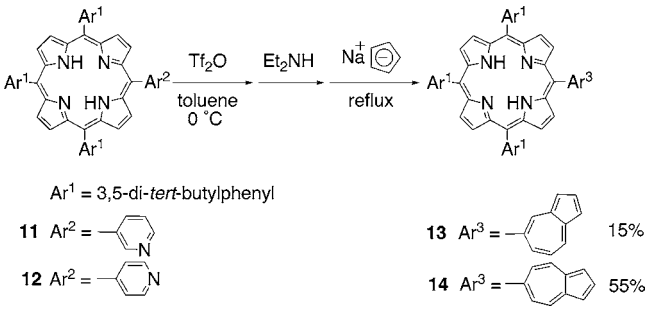
(13) Tsuda, A.; Sakamoto, S.; Yamaguchi, K.; Aida, T. *J. Am. Chem. Soc.* **2003**, *125*, 15722.

12, azulenylporphyrin **14** was obtained in 55% yield. In contrast, azulenylporphyrin was not obtained from the reaction of *meso*-(2-pyridyl)porphyrin. The dyads **13** and **14** were quantitatively converted into their Zn(II) complexes **3** and **4** by metalation with $Zn(OAc)_2$.

Scheme 2



In the ^{1}H NMR spectrum of **3**, the H^4-proton appears as singlet at 9.39 ppm; the H^1-, H^2-, and H^3-protons appear as mutually coupled signals at 7.50, 8.12, and 7.69 ppm; and H^6-, H^7-, and H^8-protons also appear as mutually coupled signals at 8.63, 7.43, and 8.75 ppm, while the proton signals of the azulenyl moiety in **4** exhibit a simple spectral feature consisting of only four signals (Supporting Information), reflecting its symmetric structure. Figure 2 shows the X-ray

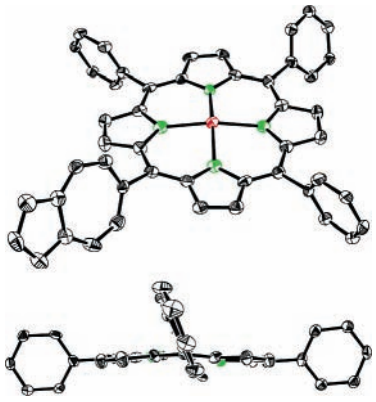


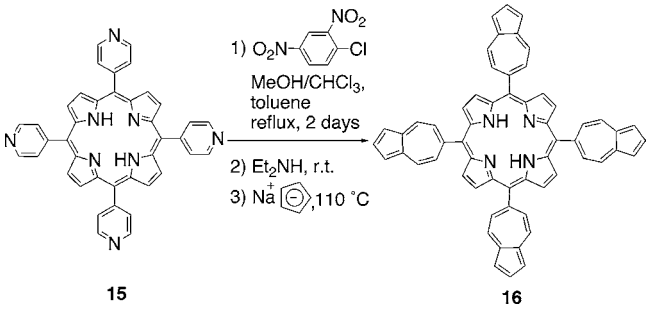
Figure 2. X-ray crystal structure of **4**. 3,5-Di-*tert*-butyl groups and hydrogen atoms are omitted for clarity.

crystal structure of **4**, in which the 6-azulenyl moiety is linked at the meso position of the porphyrin with a C−C bond length of 1.49 Å and a dihedral angle of 61°. Other C(meso)−C(aryl-ipso) bond lengths are 1.48, 1.48, and 1.49 Å, and dihedral angles are 73°, 59°, and 73° for 10-, 15-, and 20-aryl substituents, respectively.[14]

(14) Crystal data of **4**: $C_{72}H_{78}N_4Zn\cdot(C_7H_8)\cdot(C_3H_7OH)\cdot(H_2O) = 1235.06$, triclinic, space group *P*-1, $Z = 2$, $a = 10.486(5)$, $b = 18.62(1)$, $c = 19.14(1)$ Å, $\alpha = 63.58(4)°$, $\beta = 85.24(4)°$, $\gamma = 83.11(4)°$, $V = 3319(3)$ Å^3, $D_{calcd} = 1.233$ g cm^{-3}, $T = 123$ K, crystal size 0.20 × 0.15 × 0.10 mm^3, $R = 0.057$, Rw = 0.061, GOF = 0.907.

Finally, we tested the Ziegler−Hafner method to 5,10,15,20-tetrakis(4-pyridyl)porphyrin **15** (Scheme 3). Addition

Scheme 3



of Tf_2O to a toluene solution of **15** led to instantaneous precipitation of the resulting salt, which precluded the transformation of the pyridyl substituents into azulenyl groups. When 1-chloro-2,4-dinitrobenzene was used as an activator, 5,10,15,20-tertrakis(6-azulenyl)porphyrin **16** was obtained in ca. 1% yield. The compound **16** exhibits its parent ion peak at $m/z = 814.3$ and its ^{1}H NMR spectrum reveals the protons at the azulenyl moiety at 7.70−8.59 ppm and the porphyrinic β-protons at 8.84 ppm as a singlet.

Electronic interactions between the azulene and porphyrin in **1**−**4** were first studied by electrochemical measurements. The oxidation and reduction potentials were measured in benzonitrile by cyclic voltammetry. The first oxidation and reduction potentials (vs ferrocene/ferrocenium) were measured to be 0.22 and −1.82 V for **1**, 0.28 and −1.73 V for **2**, 0.28 and −1.77 for **3**, and 0.31 and −1.72 V for **4**, respectively, while the reference tetrakis(3,5-di-*tert*-butylphenyl) Zn(II)-porphyrin **17** exhibited peaks at 0.28 and −1.80 V. Consistent with the most electron-rich 1-position of azulene, both the first oxidation potential and reduction potentials of **1** were shifted to lower values in comparison to those of **17**. Conversely, consistent with the most electron-deficient 6-position of azulene, both the first oxidation and reduction potentials of **4** were shifted to higher values. On the other hand, the dyads **2** and **3** exhibited the same oxidation potentials and slightly higher reduction potentials as compared with those of **17**. In summary, the redox potentials of porphyrin were not significantly altered by the meso azulenyl group since the azulene moiety is tilted with respect to porphyrin plane. Despite this situation, as demonstrated for **1** and **4**, 1-azulenyl and 6-azulenyl moieties indeed act as electron-donating and electron-accepting substituents toward the porphyrin ring, respectively.

Next, the impact of the attached azulene moiety to the electronic system of porphyrin has been examined by the absorption and fluorescence spectra. Notably, the Soret bands of all azulenylporphyrins **1**−**4** exhibit substantial red-shifts and broadening. This is in sharp contrast to the corresponding *meso*-imide linked Zn(II)porphyrins,[15] which do not exhibit any significant red-shifts and broadening. Almost no impact of the attached imide has been interpreted in terms of the

almost perpendicular conformation of the attached imide and the node at the attached nitrogen atom of the imide moiety in the LUMO orbital. As shown in Figure 3, the order of

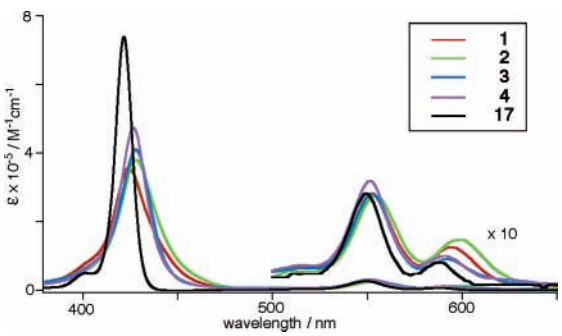


Figure 3. Absorption spectra of *meso*-azulenylporphyrins (**1**−**4**) and **17** in CH_2Cl_2.

red-shift in the Soret band is **2** (428 nm) ≈ **3** (428 nm) > **4** (427 nm) > **1** (424 nm) and the broadening is most prominent in **1** in the series. The spectral changes in the Q-band region are modest but distinct red-shifts are detected in order of **2** > **1** > **4** > **3**.

The fluorescence spectra of **1**−**4** were measured by excitation at 428 nm in CH_2Cl_2 (Supporting Information). In contrast to the variance of the Q-band positions of **1**−**4**, these dyads show fluorescence emission nearly at the same position, 602 and 649 nm, but with significant quenching that depends on the attached position. Fluorescence intensities of **1**−**4** relative to that of **17** are 0.0037, 0.0025, 0.035, and 0.0085, respectively, and the fluorescence quantum yields, as determined with respect to Zn(II) TPP in benzene (Φ_F = 0.033) as a reference,[16] are 2.1×10^{-4}, 1.7×10^{-4}, 1.7×10^{-3}, and 4.1×10^{-4} for **1**, **2**, **3**, and **4**, respectively. The fluorescence quenching is more efficient in **1** and **2**, in which the azulene moiety is linked at the five-membered ring. Although the mechanism of this fluorescence quenching has not been clarified yet, one plausible quenching route is excitation energy transfer from the S_1-state of porphyrin to the S_1-state of the attached azulene, considering a very low lying azulene S_1-state (1.77 eV)[17] compared to that (2.09 eV) of Zn(II) porphyrin.

In summary, the *meso*-azulenylporphyrins **1**−**4** were synthesized. 1-Azulenyl and 6-azulenyl substituents attached at the *meso*-position indeed lift or lower the oxidation and reduction potentials of Zn(II) porphyrin, despite having the same substituent condition. The fluorescence of Zn(II) porphyrin is quenched depending upon the substitution position of the azulene in the order of **2** > **1** > **4** > **3**. Exploration of more functional porphyrin-azulene composites as well as detailed study on the ultrafast photophysics of **1**−**4** are actively in progress in our laboratory.

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Supporting Information Available: Synthetic procedures, X-ray analysis, and spectral data. This material is available free of charge via the Internet at http://pubs.acs.org.

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