ORGANIC LETTERS

2012
Vol. 14, No. 11
2778–2781

Direct *meso*-Alkynylation of Porphyrins Doubly Assisted by Pyridyl Coordination

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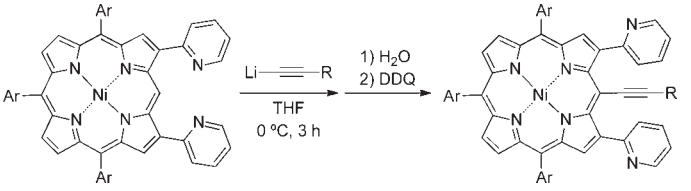
Received April 17, 2012

ABSTRACT



Direct *meso*-alkynylation of β,β'-dipyridylporphyrin with various alkynyllithium reagents has been achieved, in which the β,β'-dipyridyl groups play an important role in facilitating the nucleophilic addition of the reagents through double coordination. This method enabled the synthesis of a *meso*-ethynylene-bridged diporphyrin.

Meso-alkynylated porphyrins have often served as an important component of conjugated porphyrin arrays[1−5] since *meso*-alkynyl substituents provide substantial electronic perturbation to porphyrins and work as an effective mediator of electronic communication. In addition, ethynyl and 1,3-butadiynyl moieties are convenient and effective construction motifs for covalent connections. So far, these *meso*-alkynylated porphyrins have been prepared by functional group transformations either from *meso*-formyl porphyrins[3] or *meso*-halogenated porphyrins,[1] or alternatively by condensations of alkynal with suitable pyrrolic precursors.[2] Direct *meso*-alkynylations of porphyrins would be desirable from the viewpoint of reaction efficiency but remain unexplored to date, to the best of our knowledge.

As an effective synthetic method, Senge et al. have developed the *meso*-functionalization reaction of porphyrins that consists of nucleophilic addition of aryl or alkyllithium reagents, protonation with water to form *meso*-substituted phlorins, and final oxidation with 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ) to furnish *meso*-substituted porphyrins.[6] This reaction is applicable to a wide range of aryl and alkyllithium reagents but not to alkynyllithium reagents.

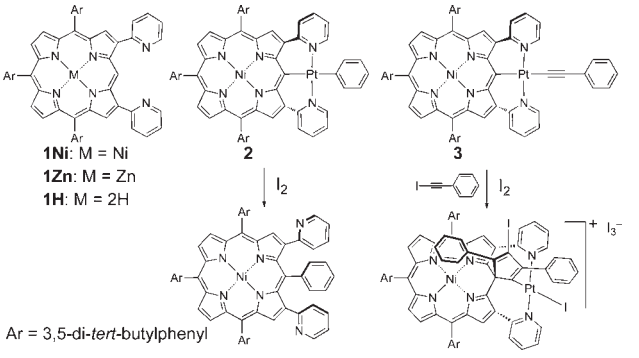


Figure 1. 2,18-Di-(2-pyridyl)porphyrin and its pincer complexes.

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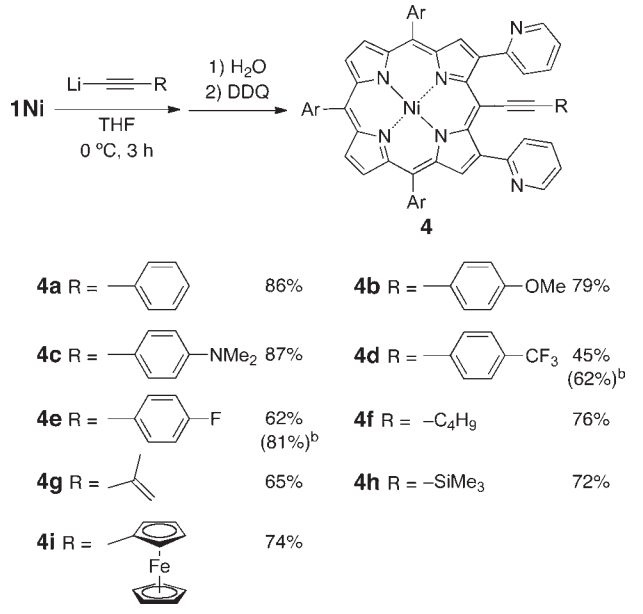
10.1021/ol301005b
Published on Web 05/17/2012

In the course of our own studies on porphyrin pincer complexes,[7−10] we prepared phenylplatinum(II) pincer complex **2** and (phenylethynyl)platinum(II) pincer complex **3** from 2,18-di-(2-pyridyl)-5,10,15-tris(3,5-di-*tert*-butylphenyl)-substituted Ni(II)porphyrin (**1Ni**)[7] and found that these pincer complexes gave different products upon oxidation with iodine (Figure 1). While **2** gave an expected *meso*-phenylated porphyrin probably via simple reductive elimination,[9] the oxidation products obtained from **3** commonly had unique structures bearing a C−C bond at the *meso* position and Pt(II) metal remained even after reductive elimination because of the strong coordination with the two pyridyl moieties.[10] Curiously, in the presence of an excess amount of phenylethynyl iodide, **3** underwent double phenylethynylation to provide a *meso*-spiro-cyclopentadienyl isoporphyrin.[10] We thought that porphyrin **1Ni** might be a nice substrate for direct nucleophilic alkynylation at the unsubstituted *meso* position owing to coordination assistance by the neighboring 2-pyridyl substituents. In this paper, we disclose a facile, direct *meso*-alkynylation reaction of **1Ni** with alkynyllithium reagents (Scheme 1).

Scheme 1. Synthesis of *meso*-Alkynyl Porphyrins[a]



[a] Ar = 3,5-di-*tert*-butylphenyl. Reaction conditions: **1Ni** (46.0 μmol), lithium reagent (5.0 equiv), DDQ (1.5 equiv), THF (4 mL), 0 °C, 3 h. [b]12 h.

First, we examined the reaction of **1Ni** with phenylethynyllithium by following Senge's protocol.[6] Namely, porphyrin **1Ni** was treated with phenylethynyllithium at 0 °C for 3 h in THF, which was followed by the addition of water and oxidation with DDQ. Gratifyingly, this reaction smoothly proceeded to provide β,β'-dipyridyl *meso*-phenylethynylporphyrin **4a** as a sole product in 86% yield (Scheme 1). The structure of **4a** is fully consistent with the spectroscopic data. High-resolution electrospray−ionization time-of-flight (HR-ESI-TOF) mass spectral analysis detected the parent ion peak of **4a** at m/z = 1185.6017 (calcd for $C_{80}H_{83}N_6Ni$ = 1185.6027 $[M + H]^+$). The ^1H NMR spectrum of **4a** exhibits the *ortho*-protons of the phenyl group at δ = 6.55 ppm, which are slightly upfield shifted as a result of the ring current of the pyridyl groups. Slow vapor diffusion of acetonitrile to a dichloroethane solution of **4a** gave nice crystals suitable for X-ray diffraction analysis. The crystal structure of **4a** revealed a *meso*-phenylethynylated skeleton unambiguously, in which the porphyrin core is distorted into a saddle conformation and the phenylethynyl group is deviated from the porphyrin mean plane due to the steric hindrance by the pyridyl groups (Figure 2).[11] In addition, the 2-pyridyl substituents take a conformation with their pyridyl nitrogen atom oppositely oriented with regard to the *meso*-alkynyl substituent.

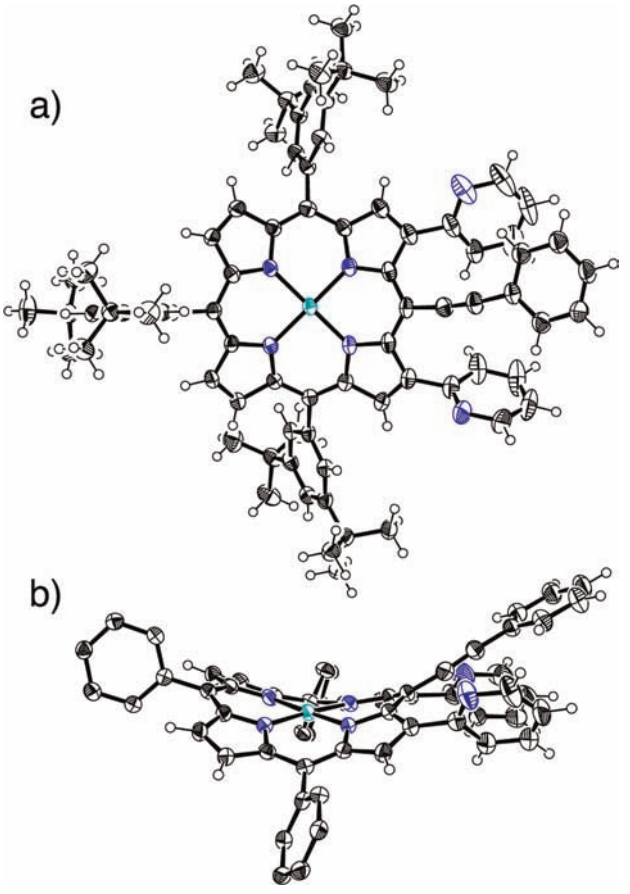


Figure 2. X-ray crystal structure of **4a**: (a) top view and (b) side view. The ellipsoids are scaled to the 50% probability. One of two porphyrins and solvent molecules are omitted for clarity. Substituents on the phenyl groups in the side view are omitted for clarity.

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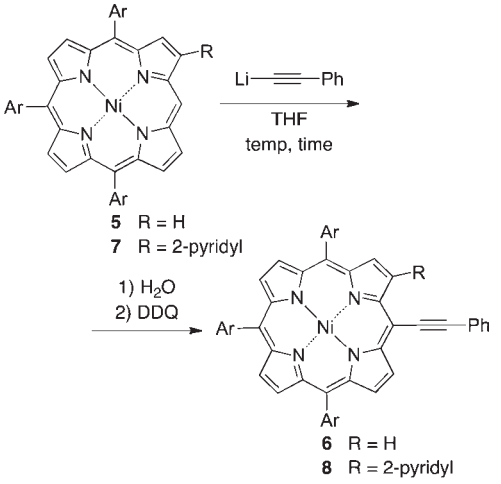
In order to study how effectively the two neighboring 2-pyridyl substituents assist the nucleophilic addition of phenylethynyllithium via coordination, we examined the reactions of porphyrin **5** and β-monopyridyl-porphyrin **7** by changing the reaction conditions (Table 1). Porphyrin **5** did not afford phenylethynylated product **6** at 0 °C or room temperature, but the reaction at 60 °C afforded **6** in 22% yield. An elongated reaction time merely resulted in complicated mixtures. A certain improvement was observed for **7**, in that the reaction of **7** at room temperature gave phenylethynylated product **8** in 23% yield. However, the reaction at 70 °C gave a complicated mixture. These results underscore the importance of two 2-pyridyl substituents for the smooth phenylethynylation reaction.

Table 1. Synthesis of *meso*-Phenylethynyl Porphyrins[a]



compd	time (h)	temp (°C)	product	yield (%)
5	3	0	**6**	0
5	3	rt	**6**	<1
5	3	60	**6**	22
5	12	60	**6**	CM
7	3	0	**8**	0
7	12	rt	**8**	23
7	12	70	**8**	CM

[a] rt = room temperature. CM = complicated mixture.

The *meso*-alkynylation reaction of **1Ni** has proven to be applicable to a wide range of alkynyllithium reagents. Both electron-rich and -deficient arylethynyllithium reagents can be employed in this reaction, giving products **4b**–**e** in good yields (Scheme 1). Due to their attenuated nucleophilicity of the electron-deficient arylethynyllithium, a longer reaction time improved the yields. 1-Hexynyllithium gave **4f** in good yield, and a conjugated alkynyllithium, 3-methylbut-3-ene-1-ynyllithium, provided **4g**. Furthermore, the reactions of trimethylsilylethynyllithium and ferrocenylethynyllithium gave **4h** and **4j** in good yields. When subjected to the comparable conditions, the corresponding Zn(II) complex **1Zn** and free base **1H** were recovered almost quantitatively. The structures of **4b** and **4h** have been also determined by X-ray analysis (Supporting Information (SI)),[12,13] with both displaying saddle-type distorted conformations, deviations of the *meso*-alkynyl substituents, and outer-orienting pyridyl groups similar to **4a**.

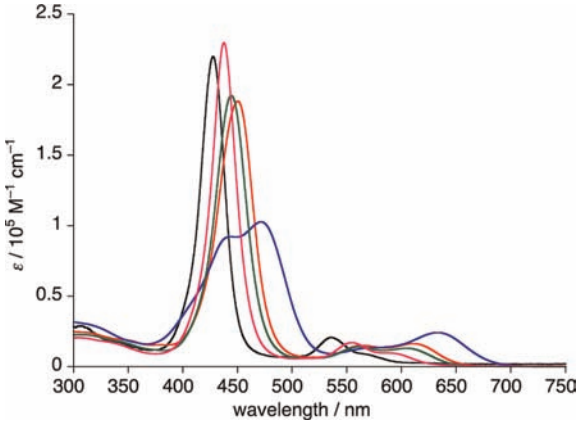


Figure 3. UV–vis absorption spectra of **1Ni** (black), **4b** (red), **4c** (blue), **4e** (green), and **4f** (pink) in CH_2Cl_2.

The *meso*-alkynylated porphyrins **4** show the perturbed and red-shifted UV–vis absorption spectra as compared with **1Ni** (Figure 3). Electron-donating arylethynyl substituents tend to shift Soret-like bands to the lower energy side. In particular, the absorption spectrum of **4c** exhibits a split and substantially red-shifted Soret band at 443 and 472 nm and a Q-band at 633 nm, probably reflecting the strong electron-donating character of the (4-dimethylaminophenyl)ethynyl substituent.

Finally, the reaction of **1Ni** with *meso*-ethynylated Ni(II) porphyrin **9** was attempted. After extensive experimentation, the use of lithium hexamethyldisilazide (LiHMDS) as a base was found to furnish *meso*-ethynylene-bridged diporphyrin **10** in 60% yield (Scheme 2). The HR-ESI-TOF

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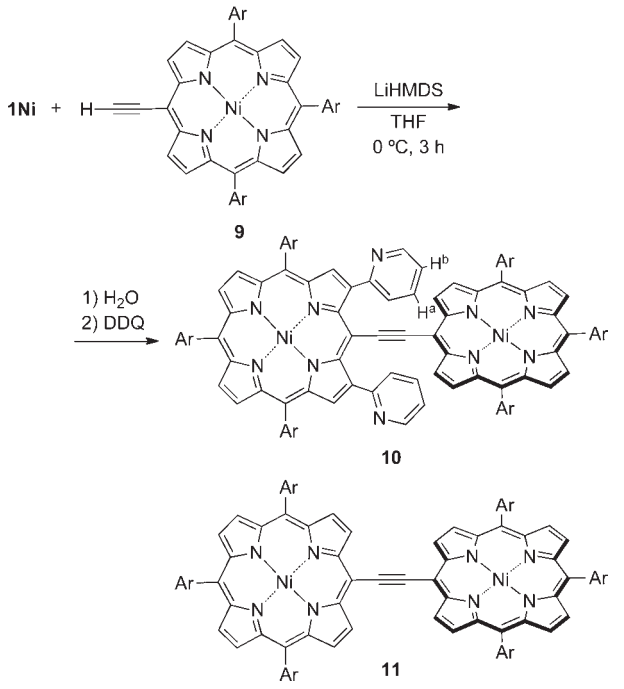
(11) Crystal data for **4a**: $C_{80}H_{82}N_6Ni\cdot(C_2H_4Cl_2)_{0.315}\cdot(CH_3CN)_3\cdot$(methanol)$_{0.185}$, M_w = 1284.17, triclinic, space group $P\bar{1}$ (no. 2), a = 14.6275(3) Å, b = 20.5197(4) Å, c = 24.8238(4) Å, α = 98.9918(7)°, β = 104.1374(7)°, γ = 94.1415(7)°, V = 7088.9(2) Å^3, Z = 4, T = 93(2) K, D_{calcd} = 1.203 g cm^{-3}, R_1 = 0.0648 ($I > 2\sigma(I)$), R_w = 0.1911 (all data), GOF = 1.077; CCDC 872911.

(12) Crystal data for **4b**: $C_{81}H_{84}N_6NiO\cdot C_6H_6$, M_w = 1294.36, triclinic, space group $P\bar{1}$ (no. 2), a = 13.467(5) Å, b = 16.348(5) Å, c = 18.590(5) Å, α = 103.845(5)°, β = 105.316(5)°, γ = 106.968(5)°, V = 3547(2) Å^3, Z = 2, T = 93(2) K, D_{calcd} = 1.212 g cm^{-3}, R_1 = 0.0430 ($I > 2\sigma(I)$), R_w = 0.1168 (all data), GOF = 1.032; CCDC 872912.

(13) Crystal data for **4h**: $C_{77}H_{86}N_6NiSi\cdot$(water)$_3$, M_w = 1294.36, orthorhombic, space group $Cmca$ (no. 64), a = 28.3019(6) Å, b = 11.8093(2) Å, c = 42.6587(8) Å, V = 14257.6(5) Å^3, Z = 8, T = 93(2) K, D_{calcd} = 1.147 g cm^{-3}, R_1 = 0.0877 ($I > 2\sigma(I)$), R_w = 0.2968 (all data), GOF = 1.065; CCDC 872910.

Scheme 2. Synthesis of Diporphyrin **10**[a]



[a] Ar = 3,5-di-*tert*-butylphenyl.

mass measurement detected the parent ion peak of **10** at m/z = 2040.0765 (calcd for $C_{136}H_{149}N_{10}Ni_2$ = 2040.0727 $[M + H]^+$). The ^1H NMR spectrum of **10** is fully consistent with its unsymmetrical structure, displaying one singlet and six doublets due to the β-protons and four signals due to the pyridyl protons (SI), among which H^a and H^b protons are observed at 6.67 and 5.67 ppm owing to the diatropic ring current of the attached porphyrin. Figure 4 shows the UV−vis absorption spectrum of **10** along with that of *meso*-ethynylene-bridged diporphyrin **11** as a reference. The absorption spectrum of **10** exhibits a broad Soret band at 446 nm and Q-bands at 548, 600, and 714 nm, which are significantly different from those of **11**. This result suggests that the diporphyrin **10** is forced to take a

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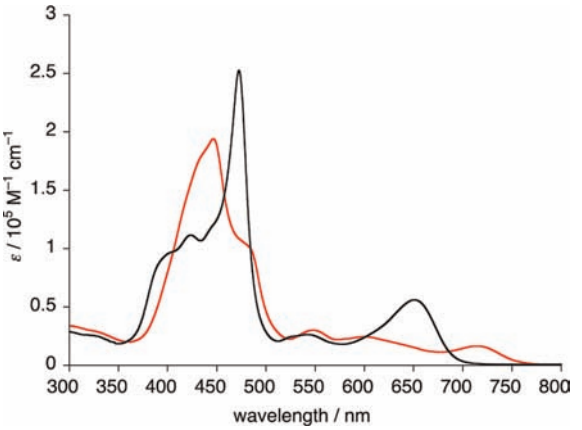

Figure 4. UV−vis absorption spectra of **10** (red) and **11** (black) in CH_2Cl_2.

restricted perpendicular conformation due to the repulsion between the appended porphyrin and two pyridyl groups.[14]

In summary, the direct *meso*-alkynylation of **1Ni** proceeded smoothly with various alkynyllithium reagents. This reaction is probably assisted by the double coordination of the pyridyl groups to the lithium reagent. The ethynylene-bridged diporphyrin **10** was prepared by this method. Coordination-assisted nucleophilic addition reactions may have wider applicability with regard to a coordinating group and nucleophile. Along this line, the application of this strategy to other useful reactions is now actively being studied in our laboratory.

Acknowledgment. This work was partly supported by Grants-in-Aid for Scientific Research (No. 18685013; Nos. 19205006 (A) and 20108001 "pi-Space") from MEXT and by the JST PRESTO program. S.T. thanks the JSPS Research Fellowship for Young Scientists program.

Supporting Information Available. Preparation and analytical data for samples, and crystallographic data (CIF). This material is available free of charge via the Internet at http://pubs.acs.org.

The authors declare no competing financial interest.