Angewandte
International Edition Chemie

DOI: 10.1002/anie.201207763

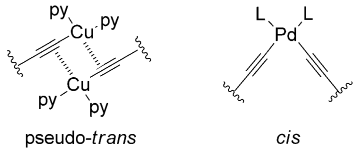
Porphyrin Macrocycles

Preferential Formation of Cyclic Trimers by Palladium-Catalyzed Oxidative Coupling Reactions of 2,18-Diethynylporphyrins**

Sumito Tokuji, Hideki Yorimitsu, and Atsuhiro Osuka**

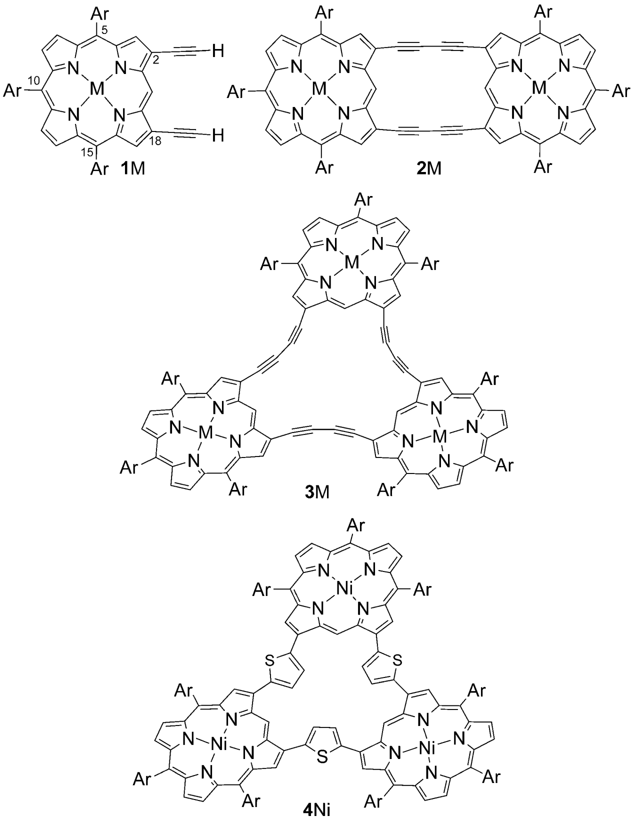
Inspired by the gigantic cyclic arrangements of bacteriochlorophylls and chlorophylls in photosynthetic light-harvesting antenna, considerable efforts have been devoted to the synthesis of cyclic porphyrin oligomers (CPOs).[1] Among these, directly 1,3-butadiyne-bridged conjugated CPOs have a special place owing to their intriguing structural, electronic, and optical properties. Usually, effective macrocyclizations require synthetic tricks. Sugiura et al. used L-shaped 5,10-diaryl-15,20-diethynylporphyrin as a key corner part for the synthesis of square *meso*-to-*meso* butadiyne-bridged planar CPOs.[2] Anderson and co-workers developed an elegant template-directed synthesis of *meso*-to-*meso* butadiyne-bridged circular CPOs using linear 5,15-diaryl-10,20-diethynylporphyrin precursors,[3] in which the structure of the template–substrate complex dictates the major CPO product. This approach has evolved into a conceptually new Vernier-template synthesis.[3d,f] We have also reported Cu-mediated oxidative dimerization reaction of 5,10,15-triaryl-2,18-diethynylporphyrins **1**M that provided β-to-β 1,3-butadiyne-bridged cyclic porphyrin dimers **2**M in good yields.[4]

It has been recognized that Pd-catalyzed oxidative coupling of acetylene can produce different products from the usual Cu-mediated reaction. As a representative example, Haley and co-workers have reported metal-dependent selective synthesis of two different dehydrobenzoannulenes by the intramolecular coupling reactions of single precursors, which is owing to the difference of their reaction mechanisms.[5] While still under debate, the mechanism of Cu-mediated oxidative butadiyne synthesis is proposed to involve a dimeric Cu acetylide arranged in a pseudo-*trans* configuration prior to reductive elimination (Scheme 1).[6] On the other hand, in Pd-catalyzed reactions, two ethynyl groups are proposed to be arranged in a *cis* geometry for reductive elimination.[7] In contrast to Haley and co-workers intramolecular reactions, metal-catalyzed intermolecular oxidative butadiyne formation is more difficult to control.[8,9] Herein, we report preferential formation of trimers **3**M by Pd-catalyzed coupling reactions of **1**M.



Scheme 1. Proposed metal acetylide intermediates in Cu-mediated (left) and Pd-catalyzed (right) reactions.

A solution of **1**Ni in toluene and diisopropylamine was stirred at room temperature in the presence of catalytic amounts of $PdCl_2(PPh_3)_2$ and CuI and two equivalents of 1,4-benzoquinone as the oxidant. Separation by preparative gel permeation chromatography provided **2**Ni[4] and **3**Ni and in 9.3 and 72% yields, respectively (Scheme 2).[10] The MALDI-TOF mass spectrum of **3**Ni displayed a parent ion peak at 2933.39 (calcd for $C_{198}H_{210}N_{12}Ni_3$, *m/z* 2933.49 $[M]^+$). The



Scheme 2. Chemical formulas of **1**M, **2**M, **3**M, and **4**Ni. Ar = 3,5-di-*tert*-butylphenyl. M = Ni, Zn, 2H.

---

[*] S. Tokuji, Prof. Dr. H. Yorimitsu, Prof. Dr. A. Osuka
Department of Chemistry, Graduate School of Science,
Kyoto University
Sakyo-ku, Kyoto 606-8502 (Japan)
E-mail: yori@kuchem.kyoto-u.ac.jp
osuka@kuchem.kyoto-u.ac.jp

[**] This work was supported by MEXT through Grants-in-Aid (Nos. 22245006 (A), 20108001 "pi-Space", and 24106721 "Reaction Integration"). S.T. acknowledges a JSPS Fellowship for Young Scientists. We thank Prof. Dr. H. Maeda and Y. Bando of Ritsumeikan University for MALDI-TOF MS measurement.

Supporting information for this article is (experimental details) available on the WWW under http://dx.doi.org/10.1002/anie.201207763.

^{1}H NMR spectrum of **3**Ni in $CDCl_3$ revealed a singlet signal at 10.35 ppm owing to the *meso* proton, reflecting its highly symmetric structure. Under similar concentrations, treatment of **1**Ni with $Cu(OAc)_2$ in pyridine/tetrahydrofuran (THF) provided **2**Ni in 82% yield with a trace amount of **3**Ni.[4] Similar results were obtained for a Zn^{II} porphyrin substrate **1**Zn; the Pd-catalyzed reaction provided **2**Zn in 24% yield and **3**Zn in 60% yield, while the Cu-mediated reaction yielded **2**Zn in 78% yield with a trace amount of **3**Zn. Demetalation of **3**Zn with hydrochloric acid provided **3**H in 54% yield.

The triangular structure of **3**Ni has been confirmed by X-ray crystallographic analysis (Figure 1).[11] The average deviation from the mean planes composed of twenty-four atoms of porphyrin cores is 0.21 Å. The averaged bond angles of $C(sp^2){-}C_\alpha{\equiv}C_\beta$ and $C_\alpha{\equiv}C_\beta{-}C_\beta$ (θ_1 and θ_2) of six non-equivalent C≡C units are 170.0° and 172.5°, respectively, hence showing a distinct deviation from the linear structure, and the average $C_\alpha{-}C_\alpha$ and $C_\beta{-}C_\beta$ distances (d_α and d_β) are 5.50 and 6.31 Å, respectively. These data indicate that the structural distortion is concentrated at the 1,3-butadiyne bridges in **3**Ni. We have also determined the X-ray crystal structures of **1**Ni and **2**Ni.[11] The distances d_α and d_β in **2**Ni are 5.29 Å and 5.37 Å, respectively, which are close to those in **1**Ni ($d_\alpha = 5.21$ Å and $d_\beta = 5.34$ Å). The averaged bond angles (θ_1 and θ_2) are 173.7° and 176.8° in **2**Ni, respectively, indicating there is less structural distortion.

Interestingly, trimer **3**Ni can be used to prepare the 2,5-thienylene-bridged triporphyrin **4**Ni. Simple heating of **3**Ni in the presence of $Na_2S{\cdot}9H_2O$ in *p*-xylene/2-methoxyethanol gave **4**Ni in 77% yield as the sole product (Scheme 2).[12] Notably, the free base trimer **4**H was prepared by Suzuki–Miyaura coupling of β,β′-diborylporphyrin with 2,5-dibromothiophene, in 10% yield along with many other porphyrin macrocycles.[13,14]

Figure 2 shows the UV/Vis absorption and fluorescence spectra of **1**Zn–**3**Zn measured in CH_2Cl_2. **3**Zn displays a highly perturbed absorption spectrum, which is similar to the case of **2**Zn. The Soret band of **3**Zn is split into two peaks at 452 and 487 nm and Q-bands are observed at 534, 566, 580 and 603 nm with a shoulder around 620 nm. This shoulder peak of **3**Zn is red-shifted as compared with that of **1**Zn (around 600 nm) but blue-shifted from that of **2**Zn (around 645 nm). The fluorescence spectrum of **3**Zn shows peak maxima at 630 and 689 nm, which are blue shifted by 27 and 43 nm, respectively, as compared with those of **2**Zn (Figure 2b). Interestingly, the fluorescence quantum yield Φ_F of **3**Zn was determined by a sphere photon-counting apparatus to be 0.056, larger than those of **1**Zn ($\Phi_F = 0.025$) and **2**Zn ($\Phi_F = 0.009$).[4] The blue shifts in the absorption and fluorescent spectra of **3**Zn may be ascribed to its less effective π conjugation as compared with **2**Zn, probably due to its distorted 1,3-butadiyne structure.

These Cu-mediated and Pd-catalyzed reactions are believed to proceed in a stepwise manner via an acyclic intermediate **2**M_AC or its related species (Scheme 3).[15] Intramolecular cyclization of **2**M_AC should be smooth in the Cu-mediated reactions through an easily available pseudo-*trans* geometry, but might be slow in the Pd-catalyzed reactions owing to difficulty in forming the requisite *cis* geometry, which would drive the intermolecular coupling reaction of **2**M_AC with another **1**M, to give the intermediate **3**M_AC. Then, the macrocyclic ring closure of **3**M_AC can proceed better, probably because **3**M_AC allows formation of the *cis* geometry that is key for the reductive elimination.[16] To confirm the stepwise mechanism, **2**Ni_AC was prepared separately (see Supporting Information) and its reactions were examined. While the Cu-mediated oxidative coupling of **2**Ni_AC provided **2**Ni in 74%, the yield of **2**Ni

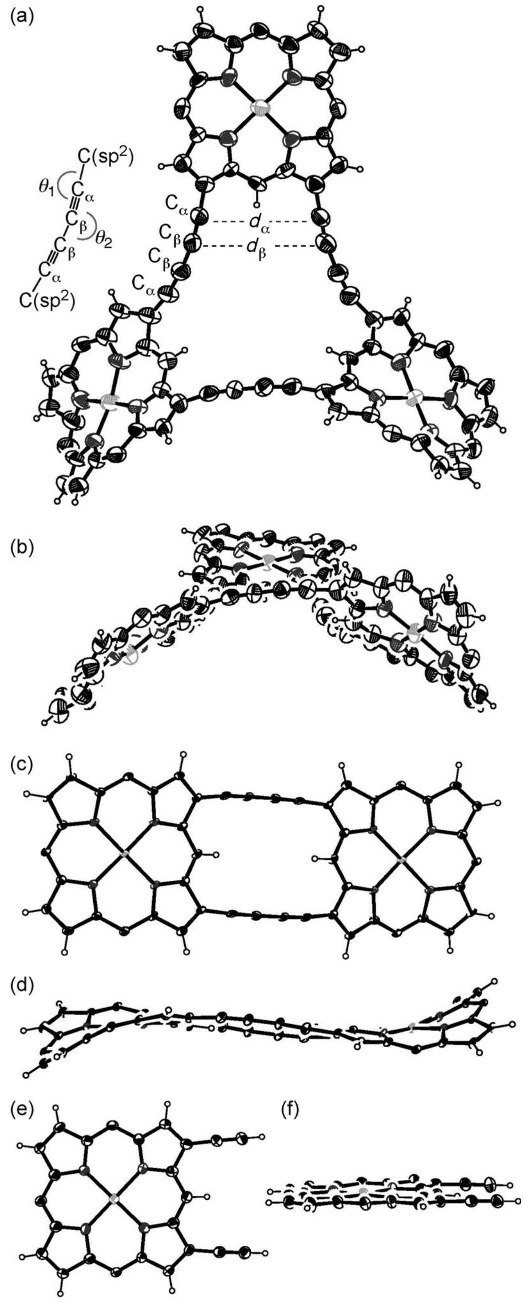


Figure 1. X-ray crystal structures. a) Top view and b) side view of **3**Ni, c) top view and d) side view of **2**Ni, e) top view and f) side view of **1**Ni. Thermal ellipsoids are shown at the 30% probability level. Solvent molecules and 3,5-di-*tert*-butylphenyl groups are omitted for clarity. Light gray spheres = Ni atoms.

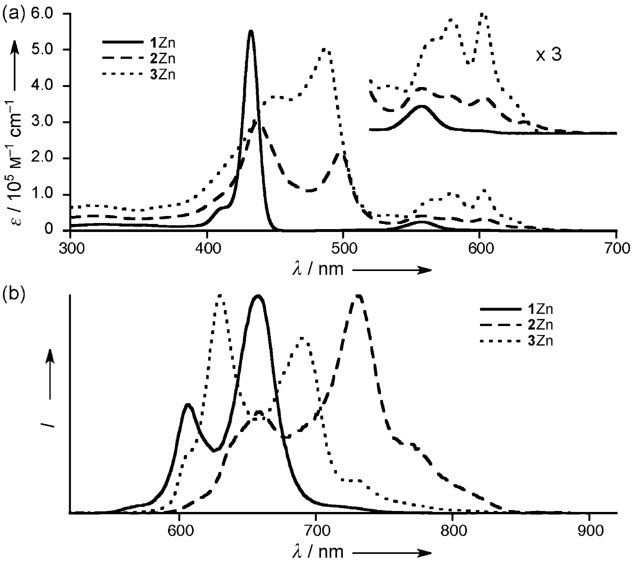
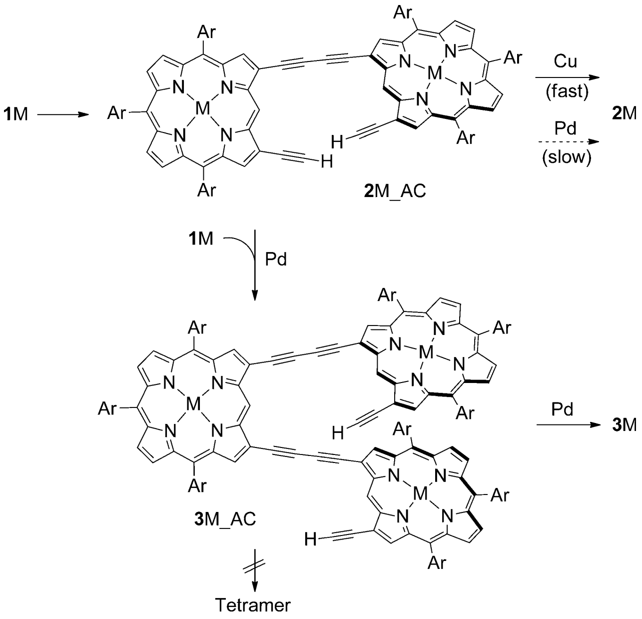


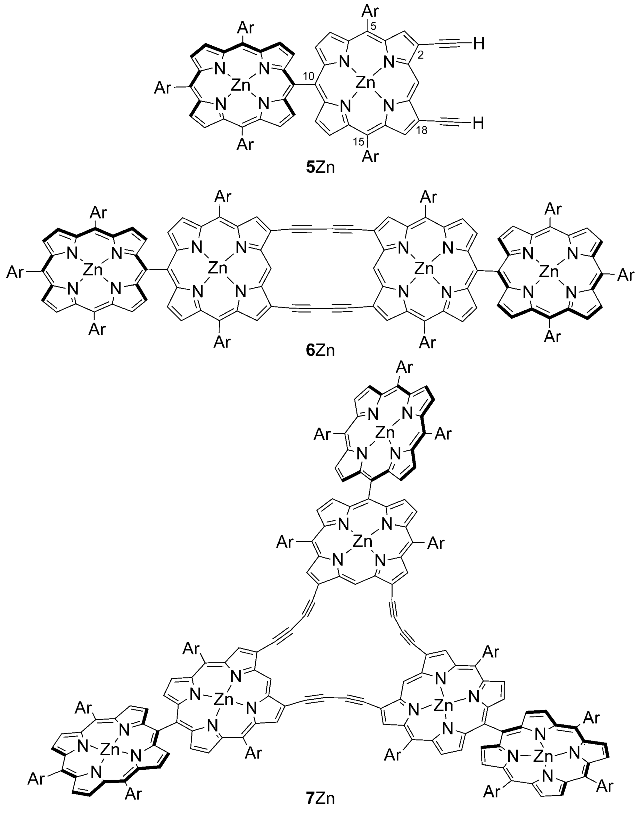
Figure 2. a) UV/Vis absorption spectra and b) fluorescence spectra of **1** Zn, **2** Zn, and **3** Zn in CH_2Cl_2. ε = molar extinction coefficient.



Scheme 3. Plausible reaction mechanisms of the Cu-mediated and Pd-catalyzed reactions. Ar = 3,5-di-*tert*-butylphenyl. M = Ni, Zn.

dropped to 44 % with various polymeric products in the Pd-catalyzed reaction. The Pd-catalyzed reaction of **1** Ni with an equimolar amount of **2** Ni_AC gave **2** Ni and **3** Ni in 20 % and 45 % yield, respectively.[17] These results are consistent with the stepwise mechanism.

Finally, this strategy was applied to a *meso–meso* directly linked diporphyrin **5** Zn. The Cu-mediated reaction of **5** Zn produced predominantly **6** Zn in 86 % yield, while the Pd-catalyzed reaction of **5** Zn provided the porphyrin hexamer **7** Zn preferentially in 54 % yield along with **6** Zn in 19 % yield (Scheme 4). These contrasting results indicate the generality of this synthetic method. The hexamer **7** Zn is attractive because of its functional similarity to the natural light-harvesting antenna in terms of possible excitation energy transfer from the peripheral porphyrins to the trimeric porphyrin core. The absorption spectra of **6** Zn and **7** Zn are roughly similar to those of **2** Zn and **3** Zn with additional contributions of the excitonically coupled *meso*-linked peripheral porphyrins (Figure 3 a). The fluorescence spec-



Scheme 4. Chemical formulas of **5** Zn, **6** Zn, and **7** Zn. Ar = 3,5-di-*tert*-butylphenyl.

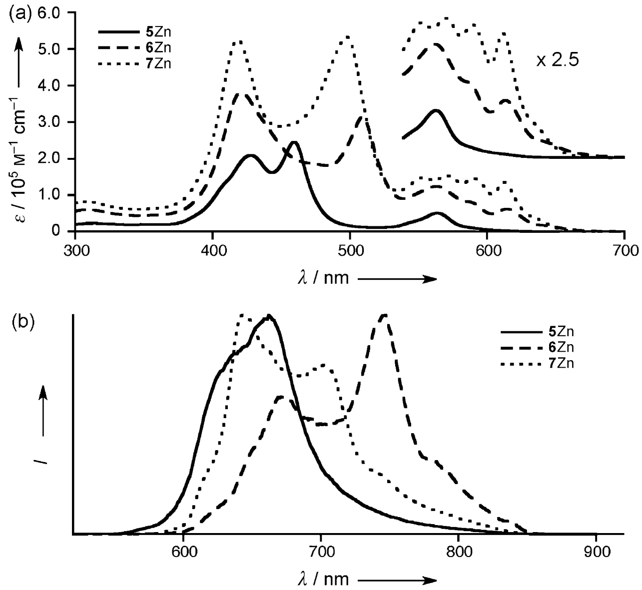


Figure 3. a) UV/Vis absorption spectra and b) fluorescence spectra of **5** Zn, **6** Zn, and **7** Zn in CH_2Cl_2.

trum of **7**Zn exhibits bands at 643 and 702 nm (Figure 3b), which are distinctly blue-shifted as compared with those of **6**Zn (674 and 747 nm), a similar trend as was observed for **2**Zn and **3**Zn. The fluorescence quantum yields are 0.038, 0.036, and 0.06 for **5**Zn, **6**Zn, and **7**Zn, respectively, again indicating that the trimeric coupling product is the most fluorescent. Collectively, these data indicate that the electronic conjugation along the 1,3-butadiyne bridges is stronger than the exciton coupling in *meso–meso*-linked diporphyrin segments.

In summary, the Pd-catalyzed oxidative coupling of 2,18-diethynylporphyrins **1**M led to the preferential formation of 1,3-butadiyne-bridged porphyrin trimers **3**M, which is complementary to Cu-mediated macrocyclization. The application of this synthetic strategy to **5**Zn provided hexaporphyrin **7**Zn as a novel light-harvesting antenna model. This strategy may be applied to other diethynylated compounds, which are actively being studied in our laboratory.

Received: September 26, 2012

Keywords: alkyne coupling · butadiyne bridge · palladium · porphyrinoids · triporphyrin synthesis

---

[1] a) S. Anderson, H. L. Anderson, J. K. M. Sanders, *Acc. Chem. Res.* **1993**, *26*, 469; b) J. Li, A. Ambroise, S. I. Yang, J. R. Diers, J. Seth, C. R. Wack, D. F. Bocian, D. Holten, J. S. Lindsey, *J. Am. Chem. Soc.* **1999**, *121*, 8927; c) Y. Kuramochi, A. Satake, Y. Kobuke, *J. Am. Chem. Soc.* **2004**, *126*, 8668; d) S. Rucareanu, A. Schuwey, A. Gossauer, *J. Am. Chem. Soc.* **2006**, *128*, 3396; e) Y. Nakamura, N. Aratani, A. Osuka, *Chem. Soc. Rev.* **2007**, *36*, 831; f) N. Aratani, D. Kim, A. Osuka, *Acc. Chem. Res.* **2009**, *42*, 1922; g) N. Aratani, A. Osuka, in *Handbook of Porphyrin Science, Vol. 1* (Eds.: K. M. Kadish, K. M. Smith, R. Guilard), World Scientific Publishing, Singapore, **2010**, pp. 1.

[2] a) K. Sugiura, Y. Fujimoto, Y. Sakata, *Chem. Commun.* **2000**, 1105; b) K. Sugiura, *Top. Curr. Chem.* **2003**, *228*, 65; c) A. Kato, K. Sugiura, H. Miyasaka, H. Tanaka, T. Kawai, M. Sugimoto, M. Yamashita, *Chem. Lett.* **2004**, *33*, 578.

[3] a) M. Hoffmann, C. J. Wilson, B. Odell, H. L. Anderson, *Angew. Chem.* **2007**, *119*, 3183; *Angew. Chem. Int. Ed.* **2007**, *46*, 3122; b) M. Hoffmann, J. Kärnbratt, M.-H. Chang, L. M. Herz, B. Albinsson, H. L. Anderson, *Angew. Chem.* **2008**, *120*, 5071; *Angew. Chem. Int. Ed.* **2008**, *47*, 4993; c) J. K. Sprafke, D. V. Kondratuk, M. Wykes, A. L. Thompson, M. Hoffmann, R. Drevinskas, W. H. Chen, C. K. Yong, J. Kärnbratt, J. E. Bullock, M. Malfois, M. R. Wasielewski, B. Albinsson, L. M. Herz, D. Zigmantas, D. Beljonne, H. L. Anderson, *J. Am. Chem. Soc.* **2011**, *133*, 17262; d) M. C. O'Sullivan, J. K. Sprafke, D. V. Kondratuk, C. Rinfray, T. D. W. Claridge, A. Saywell, M. O. Blunt, J. N. O'Shea, P. H. Beton, M. Malfois, H. L. Anderson, *Nature* **2011**, *469*, 72; e) J. K. Sprafke, B. Odell, T. D. W. Claridge, H. L. Anderson, *Angew. Chem.* **2011**, *123*, 5687; *Angew. Chem. Int. Ed.* **2011**, *50*, 5572; f) D. V. Kondratuk, L. M. A. Perdigao, M. C. O'Sullivan, S. Svatek, G. Smith, J. N. O'Shea, P. H. Beton, H. L. Anderson, *Angew. Chem.* **2012**, *124*, 6800; *Angew. Chem. Int. Ed.* **2012**, *51*, 6696.

[4] I. Hisaki, S. Hiroto, K. S. Kim, S. B. Noh, D. Kim, H. Shinokubo, A. Osuka, *Angew. Chem.* **2007**, *119*, 5217; *Angew. Chem. Int. Ed.* **2007**, *46*, 5125.

[5] a) J. A. Marsden, J. J. Miller, M. M. Haley, *Angew. Chem.* **2004**, *116*, 1726; *Angew. Chem. Int. Ed.* **2004**, *43*, 1694; b) J. A. Marsden, J. J. Miller, L. D. Shirtcliff, M. M. Haley, *J. Am. Chem. Soc.* **2005**, *127*, 2464; c) J. A. Marsden, M. M. Haley, *J. Org. Chem.* **2005**, *70*, 10213; d) C. A. Johnson II, M. M. Haley, *Organometallics* **2005**, *24*, 1161; e) E. L. Spitler, J. M. Monson, M. M. Haley, *J. Org. Chem.* **2008**, *73*, 2211; f) T. Takeda, A. G. Fix, M. M. Haley, *Org. Lett.* **2010**, *12*, 3824.

[6] a) F. Bohlmann, H. H. Schönowsky, E. Inhoffen, G. Grau, *Chem. Ber.* **1964**, *97*, 794; b) P. Siemsen, R. C. Livingston, F. Diederich, *Angew. Chem.* **2000**, *112*, 2740; *Angew. Chem. Int. Ed.* **2000**, *39*, 2632; c) L. Fomina, B. Vazquez, E. Tkatchouk, S. Fomine, *Tetrahedron* **2002**, *58*, 6741.

[7] a) A. Gillie, J. K. Stille, *J. Am. Chem. Soc.* **1980**, *102*, 4933; b) F. Ozawa, T. Ito, Y. Nakamura, A. Yamamoto, *Bull. Chem. Soc. Jpn.* **1981**, *54*, 1868; c) J. J. Low, W. A. Goddard III, *J. Am. Chem. Soc.* **1986**, *108*, 6115; d) J. M. Brown, N. A. Cooley, *Chem. Rev.* **1988**, *88*, 1031.

[8] S. S. Jester, N. Shabelina, S. M. L. Blanc, S. Höger, *Angew. Chem.* **2010**, *122*, 6237; *Angew. Chem. Int. Ed.* **2010**, *49*, 6101.

[9] In the case of dibenz[*a,j*]anthracene-based macrocycle formations, dimers were the main products; J. M. W. Chan, J. R. Tischler, S. E. Kooi, V. Bulovic, T. M. Swager, *J. Am. Chem. Soc.* **2009**, *131*, 5659.

[10] Use of a catalyst bearing a *cis*-bidentate ligand $PdCl_2$(dppf)led to decreased yields of **3**Ni (14%) and **2**Ni (18%) along with polymerized products (see Supporting Information).

[11] Crystallographic data for **3**Ni: $C_{198}H_{210}N_{12}Ni_3$, $M_w = 2933.91$, monoclinic, space group *C2/c* (No. 15), $a = 65.51(3)$, $b = 24.309(7)$, $c = 31.96(2)$ Å, $\beta = 113.67(5)°$, $V = 46614(43)$ Å^3, $Z = 8$, $D_{calc} = 0.836$ g cm^{-3}, $T = 93(2)$ K, $R_1 = 0.1121$ ($I > 2.0\sigma(I)$), $R_w = 0.2532$ (all data), GOF = 1.151 ($I > 2.0\sigma(I)$). Some unassigned electron density owing to severely disordered solvent was removed by using the utility SQUEEZE in the PLATON software package;[18] Crystallographic data for **2**Ni: $C_{132}H_{140}N_8Ni_2$, $6(C_6H_4Cl_2)$, $M_w = 1418.95$, triclinic, space group *P*-1 (No. 2), $a = 11.9002(2)$, $b = 16.0714(3)$, $c = 20.3575(4)$ Å, $\alpha = 88.0309(10)$, $\beta = 74.0268(10)$, $\gamma = 79.8791(16)°$, $V = 3684.46(12)$ Å^3, $Z = 2$, $D_{calc} = 1.279$ g cm^{-3}, $T = 93(2)$ K, $R_1 = 0.0949$ ($I > 2.0\sigma(I)$), $R_w = 0.2843$ (all data), GOF = 1.073 ($I > 2.0\sigma(I)$); Crystallographic data for **1**Ni: $C_{66}H_{72}N_4Ni$, $2.5(C_2H_4Cl_2)$, $M_w = 1227.37$, triclinic, space group *P*-1 (No. 2), $a = 10.6798(4)$, $b = 17.1731(6)$, $c = 18.9668(6)$ Å, $\alpha = 70.036(2)$, $\beta = 81.909(2)$, $\gamma = 87.581(2)°$, $V = 3236.97(19)$ Å^3, $Z = 2$, $D_{calc} = 1.259$ g cm^{-3}, $T = 93(2)$ K, $R_1 = 0.0954$ ($I > 2.0\sigma(I)$), $R_w = 0.2443$ (all data), GOF = 1.037 ($I > 2.0\sigma(I)$). CCDC 899883 (**3**Ni), 899882 (**2**Ni) and 899881 (**1**Ni) 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.

[12] For transformation of 1,3-butadiynes to thiophenes, see a) J. Krömer, I. Rios-Carreras, G. Fuhrmann, C. Musch, M. Wunderlin, T. Debaerdemaeker, E. Mena-Osteritz, P. Bäuerle, *Angew. Chem.* **2000**, *112*, 3623; *Angew. Chem. Int. Ed.* **2000**, *39*, 3481; b) J. Lagan, S. K. Arora, *J. Org. Chem.* **1983**, *48*, 4317; c) N. Sumi, H. Nakanishi, S. Ueno, K. Takimiya, Y. Aso, T. Otsubo, *Bull. Chem. Soc. Jpn.* **2001**, *74*, 979; d) M. J. O'Connor, M. M. Haley, *Org. Lett.* **2008**, *10*, 3973; e) C. Maeda, T. Yoneda, N. Aratani, M.-C. Yoon, J. M. Lim, D. Kim, N. Yoshioka, A. Osuka, *Angew. Chem.* **2011**, *123*, 5809; *Angew. Chem. Int. Ed.* **2011**, *50*, 5691.

[13] J. Song, S. Y. Jang, S. Yamaguchi, J. Sankar, S. Hiroto, N. Aratani, J.-Y. Shin, S. Easwaramoorthi, K. S. Kim, D. Kim, H. Shinokubo, A. Osuka, *Angew. Chem.* **2008**, *120*, 6093; *Angew. Chem. Int. Ed.* **2008**, *47*, 6004.

[14] Suzuki–Miyaura coupling of β,β'-diboryl Ni^{II} porphyrin with bromo(*tert*-butyldimethylsilyl)acetylene and subsequent desilylation with tetrabutylammonium floride (TBAF) provided **1**Ni in 72% yield (Supporting Information).

[15] These Pd-catalyzed or Cu-mediated reactions are different from the Bäuerle's case, in which pre-organization of Pt complexes enabled macrocycle formations. See Ref. [12a].

[16] For ring-closure processes, Pd-catalyzed acetylene coupling reactions were sometimes adopted. See Refs [3,5] and a recent review; M. Iyoda, J. Yamakawa, M. J. Rahman, *Angew. Chem.* **2011**, *123*, 10708; *Angew. Chem. Int. Ed.* **2011**, *50*, 10522.

[17] The yields were calculated on the basis of the number of porphyrin subunits.

[18] a) A. L. Spek, *PLATON, A Multipurpose Crystallographic Tool*, Utrecht University, Utrecht, The Netherlands, **2005**; b) P. van der Sluis, A. L. Spek, *Acta Crystallogr. Sect. A* **1990**, *46*, 194.