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Regioselective [3+4] cycloaddition of an azomethine ylide to *meso–meso*, β–β, β′–β′ triply linked diporphyrins

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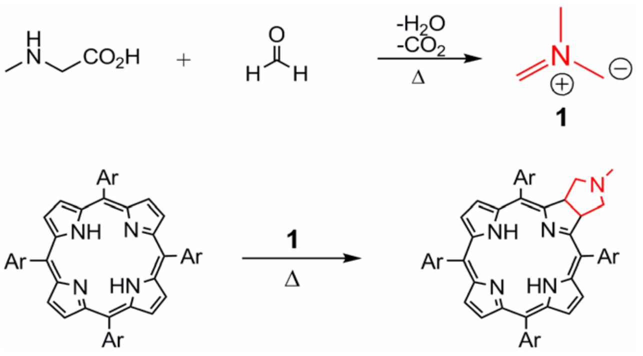
Abstract

Thermal reaction of *meso–meso*, β–β, β′–β′ triply linked diporphyrins with an azomethine ylide produced seven-membered cycloadducts via formal [3+4] cycloaddition at the bay-area. Bischlorin structures of the cycloadducts are characterized on the basis of spectroscopic data and confirmed by single crystal X-ray diffraction analysis. Interestingly, the stability of the cycloadducts depends on the central metal ions in the porphyrin core.

In recent years, conjugated porphyrin arrays have been extensively explored in light of their potential applications in optoelectronic devices, photovoltaic devices, nonlinear optical materials, photodynamic therapy, and so on.[1,2] Among these, we reported *meso–meso*, β–β, β′–β′ triply linked porphyrin arrays (porphyrin tapes) that have strongly conjugated electronic networks as demonstrated by remarkable red shifts for the absorption Q-like bands of the longer porphyrin tapes, typically an intensified Q-like band at 3500 cm^{-1} for a dodecamer.[3] Porphyrin tapes exhibit unique properties including red-shifted and strongly perturbed absorption bands,[3] fluorescence in near infrared-region,[4,5a] large two-photon absorption cross-section,[6] multicharge storage,[5b] and electrochemically communicative guest binding.[7] Despite these promises, there are only a few synthetic methods that modify the periphery of porphyrin tapes and thus create novel π-conjugated functional porphyrins.

Recently, we found that the cycloaddition reactions of triply linked Zn(II) diporphyrin with *o*-xylylene proceed regioselectively at the bay-area to provide [4+2] and [4+4] cycloadducts.[8] The latter product results from a symmetry-forbidden thermal process, hence underscoring the unique reactivity of the porphyrin tapes. As an extension of this research, we now examined the thermal reaction of porphyrin tapes with azomethine ylide **1** as a 1,3-dipole. Azomethine ylide **1** reacts with *meso*-tetraarylporphyrins to provide pyrrolidine-fused cycloadducts (Scheme 1),[9] and the reaction of [36] octaphyrin(1.1.1.1.1.1.1.1) with **1** afforded pyrrolidine-fused cycloadducts in good yields,[10] both via a symmetry-allowed normal 1,3-dipolar cycloaddition route.

Here, we employed triply linked Zn(II) diporphyrin **2** as a substrate because of its nice solubility and high structural



Scheme 1. 1,3-Dipolar cycloaddition reaction of **1** and *meso*-aryl porphyrin.

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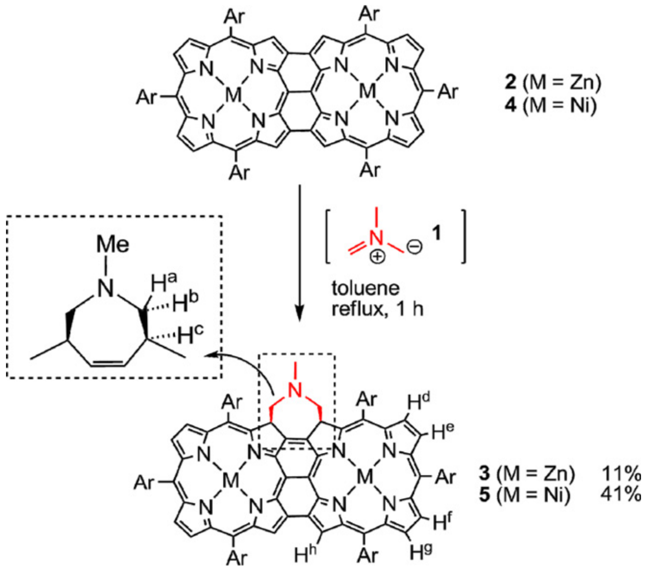


Scheme 2. 1,3-Dipolar cycloaddition reaction of *meso–meso*, β–β, β′–β′ triply linked diporphyrin with azomethine ylide. Ar = 3,5-di-*tert*-butylphenyl.

symmetry. Sarcosine (2.5 equiv) and para-formaldehyde (6 equiv) were added to a toluene solution of **2** under nitrogen atmosphere and the resulting solution was refluxed for 1 h (Scheme 2). TLC analysis of the reaction mixture revealed that two new spots appeared besides the starting material **2**, a green fraction and a dark red colored fraction. These two fractions were separated by silica gel column chromatography. MALDI-TOF mass analysis revealed that the former is a 1:1 adduct and the latter is a 1:2 adduct. The ^{1}H NMR spectrum of the dark red colored fraction was very complicated, presumably indicating the formation of a mixture of several regioisomeric bis-adducts, and thus further analysis of these products was difficult. The green fraction that was isolated in less than 5% yield exhibited the parent ion peaks at m/z = 1928.0297 (calcd for $C_{127}H_{145}N_9Zn_2$ = 1928.0204 $[M]^+$) in the high-resolution electrospray-ionization time-of-flight (HR-ESI-TOF) mass spectrum, in accordance with its assignment as a 1:1 adduct **3**. The ^{1}H NMR spectrum of **3** in $CDCl_3$ exhibits a simple feature consisting of four doublet signals for the outer eight β protons at 8.38, 8.34, 8.21, and 8.19 ppm (H^d, H^e, H^f, and H^g) and a singlet signal for the inner two β protons at 9.17 ppm (H^h). In addition, a double doublet signal at 6.87 ppm (H^c) for the inner two sp^3 β protons and two double doublet signals at 3.55 and 3.20 ppm (H^b and H^a) for the bridging methylene protons were observed. These data indicate a symmetric structure of **3**, which is resulted from cycloaddition at the bay-area (See Supporting Information, SI).[11] Unfortunately, adduct **3** is unstable in the air, possibly due to its easily oxidizable nature. We found that **3** gradually reverted to **2** just upon standing in the air, while it can be stored for a longer time under deaerated conditions at low temperature.

Triply linked Ni(II) diporphyrin **4** underwent the similar cycloaddition with **1** to provide **5**, which was thermally stable and thus easier to handle. In the synthetic procedure, an additional stirring for 1 h after heating improved the yield to 41%. Using the same procedure, the yield of **3** was also improved to 11% but the instability of **3** interrupted further improvement. The parent ion peak of **5** was detected by HR-ESI-TOF mass measurement at m/z = 1915.0391 (calcd for $C_{127}H_{146}N_9Ni_2$ = 1915.0420 $[M+H]^+$). The ^{1}H NMR spectrum is essentially the same as that of **3**.[12] The structure of **5** has been unambiguously revealed by single crystal X-ray diffraction analysis (Fig. 1).[13] A 2,3,6,7-tetrahydroazepine segment is symmetrically fused at the bay-area across the two porphyrins to form two chlorins. The bischlorin molecular shape is roughly rectangular with a 6.9 × 15.2 Å size and planar with a small mean plane deviation of 0.068 Å, to which the tetrahydroazepine segment is fused with a dihedral angle of 54°. It is interesting to note that the vertical dispositions of the Ni atoms are exceptionally small, only 0.022 Å from the mean plane defined by the chlorin macrocycle. Ni–N bond distances are in 1.96–1.97 Å, which are distinctly longer than those in Ni(II) TPP (ca. 1.93 Å).[14] These structural variations may be caused by the fused tetrahydroazepine segment.

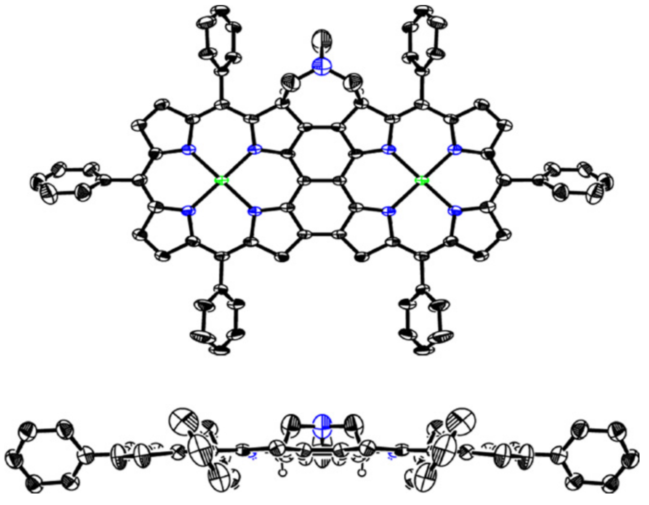


Fig. 1. ORTEP representation of X-ray crystal structure of **5**: a top view (upper) and a side view (bottom). Thermal ellipsoids are 50% probability. Hydrogen atoms, *tert*-butyl substituents, and solvent molecules are omitted for clarity.

The absorption spectra of **2**, **3**, **4**, and **5** in $CHCl_3$ was shown in Figure 2. The absorption spectra of **3** and **5** are complicated as compared with those of **2** and **4**, due to the symmetry lowering associated with the bischlorin constitutions. The spectral features of **3** and **5** are similar to those of the previously reported bischlorin cycloadducts in terms of split Soret-like band and complicated Q-like bands.[8] A peculiar feature is a low-energy Q-band like absorption band observed at 1053 nm for **3**. Interestingly, such an absorption band is weak and blue-shifted for **5**.

In the next step, we examined the oxidation of **3** and **5** to synthesize the corresponding bisporphyrin compounds by using 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ),

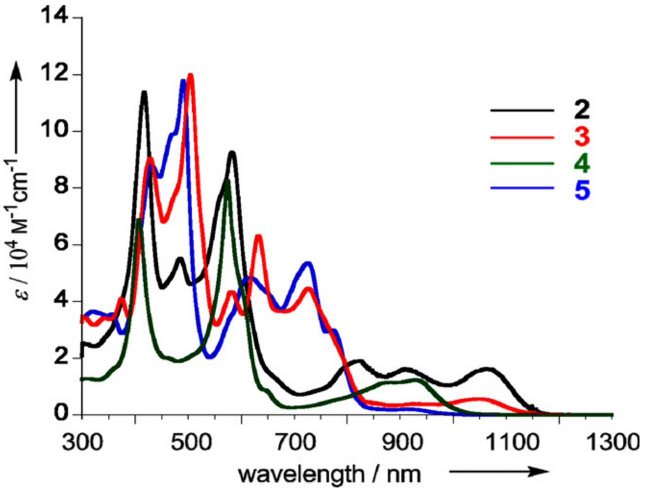


Fig. 2. UV/vis absorption spectra of **2**, **3**, **4**, and **5** in $CHCl_3$.

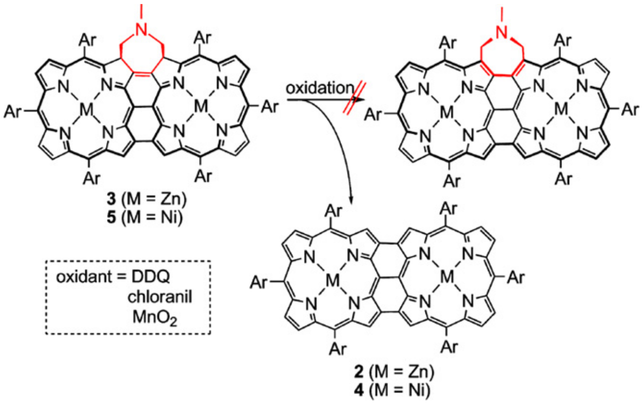
2,3,5,6-tetrachloro-1,4-benzoquinone (chloranil), and MnO_2. All of these trials failed, merely producing the starting materials **2** and **4** quantitatively (Scheme 3). These results indicate particular chemical instabilities of the [3+4] cycloadducts under oxidation conditions.

Table 1
Cyclic voltammetry data of **2**, **3**, **4**, and **5**

	$E^{1/2}_{\mathrm{ox},3}$	$E^{1/2}_{\mathrm{ox},2}$	$E^{1/2}_{\mathrm{ox},1}$	$E^{1/2}_{\mathrm{red},1}$	$E^{1/2}_{\mathrm{red},2}$
2	1.14	0.75	0.15	—	—
3	0.63	0.37	0.05	−0.52	−0.84
4	0.92	0.61	0.24	−1.14	—
5	0.97	0.64	0.28	−1.13	—

Potential versus Fc/Fc^+. Working electrode: glassy carbon electrode, counter electrode: Pt electrode, reference electrode: $Ag/AgClO_4$ electrode, solvent: CH_2Cl_2 (+0.1 M Bu_4NBF_4), $E^{1/2} = (E_{pc} + E_{pa})/2$, where E_{pc} and E_{pa} are cathodic and anodic peak potentials.

In order to understand a marked difference in the stability between **3** and **5**, the electrochemical properties were examined by cyclic voltammetry (Table 1). It has been revealed that there are three reversible oxidation waves, at 0.05, 0.37, and 0.63 V for **3** and at 0.28, 0.64, and 0.97 V for **5**, and the reversible reduction waves are observed at −0.52 V for **3** and −1.13 V for **5**, respectively, in CH_2Cl_2. These electrochemical data feature the different influence of a structural change from bisporphyrin to bischlorin. The first oxidation potential of **3** is considerably low, hence explaining its instability under oxidizing conditions, while the first oxidation potential of **5** is shifted slightly to positive from **4**. The relatively high oxidation potential of **5** may account for its stability toward the oxidative reversion. The observed different influence in the first oxidation potential is unique. Particularly, the slight positive shift of the first oxidation potentials from **4** to **5** is opposite to the known trend of distinct negative shifts from Ni(II) porphyrins to Ni(II) chlorins.[15] This may be ascribed to the unique structure of the tetrapyrrolic binding pocket of **5**, which is modified upon the fusion of the azomethine ylide. Actually, as mentioned above, **5** nicely accommodates Ni(II) ion without any noticeable distortion, which is different from the usual Ni(II) porphyrins.[3d]



Scheme 3. Attempted oxidations of **3** and **5**.

Finally, it is worthy to note that the 1,3-dipolar cycloadditions of **2** and **4** with **1** proceed regioselectively at the bay-area, similarly to the [4+4] cycloaddition reaction of triply linked diporphyrins with *o*-xylylene. This regioselectivity has been ascribed, as reported previously, to the calculated large electron densities of the HOMO and LUMO at the bay-area.[8] It is also important to note that the cycloadditions of **2** and **4** with **1** are unusual, in that the products are formally symmetrically forbidden [3+4] cycloadducts, which are quite rare in the literature.[16] We believe that this unprecedented reactivities of the triply linked diporphyrins **2** and **4** are stemming from the unique, extremely delocalized electronic properties.

In summary, the triply linked diporphyrins **2** and **4** underwent rare regioselective [3+4] cycloaddition reaction with the 1,3-dipolar azomethine ylide **1**. Cycloadducts **3** and **5** have bischlorin structures, which have been well characterized by their ^1H NMR, cyclic voltammetry, UV/vis absorption spectra, and single crystal X-ray diffraction analysis. These results highlight the unique reactivities of the triply linked diporphyrins towards 1,3-dipole, which will be used to fabricate the triply linked diporphyrins for exploring novel conjugated systems. Now, experimental studies are underway to examine the mechanistic details and to explore novel conjugated systems from the related cycloadditions of triply linked diporphyrin.

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Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.tetlet.2008.03.057.

References and notes

1. (a) Crossley, M. V.; Burn, P. L. *J. Chem. Soc., Chem. Commun.* **1991**, 1569; (b) Lin, V. S.-Y.; DiMagno, S. G.; Therien, M. J. *Science* **1994**, *264*, 1105; (c) Vicente, M. G. H.; Jaquinod, L.; Smith, K. M. *Chem. Commun.* **1999**, 1771; (d) Anderson, H. L. *Chem. Commun.* **1999**, 2323; (e) Holten, D.; Bocian, D. F.; Lindsey, J. S. *Acc. Chem. Res.* **2002**, *35*, 57; (f) Sugiura, K.; Fujimoto, Y.; Sakata, Y. *Chem. Commun.* **2000**, 1105; (g) Uno, H.; Matsumoto, A.; Ono, N. *J. Am. Chem. Soc.* **2003**, *125*, 12082; (h) Richeter, S.; Jeandon, C.; Gisselbrecht, J.-P.; Ruppert, R.; Callot, H. J. *J. Am. Chem. Soc.* **2002**, *124*, 6168; (i) Susumu, K.; Frail, P. R.; Angiolillo, P. J.; Therien, M. J. *J. Am. Chem. Soc.* **2006**, *128*, 8380; (j) Hoffmann, M.; Wilson, C. J.; Odell, B.; Anderson, H. L. *Angew. Chem., Int. Ed.* **2007**, *46*, 3122.
2. (a) Tsuda, A.; Nakano, A.; Furuta, H.; Yamochi, H.; Osuka, A. *Angew. Chem., Int. Ed.* **2000**, *39*, 558; (b) Kurotobi, K.; Kim, K. S.; Noh, S. B.; Kim, D.; Osuka, A. *Angew. Chem., Int. Ed.* **2006**, *45*, 3944; (c) Nakamura, Y.; Aratani, N.; Shinokubo, H.; Takagi, A.; Kawai, T.; Matsumoto, T.; Yoon, Z. S.; Kim, D. Y.; Ahn, T. K.; Kim, D.; Muranaka, A.; Kobayashi, N.; Osuka, A. *J. Am. Chem. Soc.* **2006**, *128*, 4119; (d) Hiroto, S.; Furukawa, K.; Shinokubo, H.; Osuka, A. *J. Am. Chem. Soc.* **2006**, *128*, 12380; (e) Hisaki, I.; Hiroto, S.; Kim, K. S.; Noh, S. B.; Kim, D.; Shinokubo, H.; Osuka, A. *Angew. Chem., Int. Ed.* **2007**, *46*, 5125.
3. (a) Tsuda, A.; Furuta, H.; Osuka, A. *Angew. Chem., Int. Ed.* **2000**, *39*, 2549; (b) Tsuda, A.; Osuka, A. *Science* **2001**, *293*, 79; (c) Tsuda, A.; Osuka, A. *Adv. Mater.* **2002**, *14*, 75; (d) Tsuda, A.; Furuta, H.; Osuka, A. *J. Am. Chem. Soc.* **2001**, *123*, 10304; (e) Hiroto, S.; Osuka, A. *J. Org. Chem.* **2005**, *70*, 4054; (f) Ikeue, T.; Aratani, N.; Osuka, A. *Israel J. Chem.* **2005**, *45*, 293.
4. Cho, H. S.; Jeong, D. H.; Cho, S.; Kim, D.; Matsuzaki, Y.; Tanaka, K.; Tsuda, A.; Osuka, A. *J. Am. Chem. Soc.* **2002**, *124*, 14642.
5. (a) Bonifazi, D.; Accorsi, G.; Armaroli, N.; Song, F.; Palkar, A.; Echegoyen, L.; Scholl, M.; Seiler, P.; Jaun, B.; Diederich, F. *Helv. Chim. Acta* **2005**, *88*, 1839; (b) Bonifazi, D.; Scholl, M.; Song, F.; Echegoyen, L.; Accorsi, G.; Armaroli, N.; Diederich, F. *Angew. Chem., Int. Ed.* **2003**, *42*, 4966.
6. (a) Kim, D. Y.; Ahn, T. K.; Kwon, J. H.; Kim, D.; Ikeue, T.; Aratani, N.; Osuka, A.; Shigeiwa, M.; Maeda, S. *J. Phys. Chem. A* **2005**, *105*, 2996; (b) Ahn, T. K.; Kim, K. S.; Kim, D. Y.; Noh, S. B.; Aratani, N.; Ikeda, C.; Osuka, A.; Kim, D. *J. Am. Chem. Soc.* **2006**, *128*, 1700.
7. (a) Sato, H.; Tashiro, K.; Shinmori, H.; Osuka, A.; Aida, T. *Chem. Commun.* **2005**, 2324; (b) Sato, H.; Tashiro, K.; Shinmori, H.; Osuka, A.; Murata, Y.; Komatsu, K.; Aida, T. *J. Am. Chem. Soc.* **2005**, *127*, 13086.
8. Tanaka, T.; Nakamura, Y.; Osuka, A. *Chem. Eur. J.* **2008**, *14*, 204.
9. Silva, A. M. G.; Tome', A. C.; Neves, M. G. P. M. S.; Silva, A. M. S.; Cavaleiro, J. A. S. *Chem. Commun.* **1999**, 1767.
10. Hata, H.; Kamimura, Y.; Shinokubo, H.; Osuka, A. *Org. Lett.* **2006**, *8*, 1169.
11. Compound data for **3**. ^{1}H NMR (CDCl$_3$, −20 °C): δ 9.17 (s, 2H, H^h), 8.38 (d, $J = 4.8$ Hz, 2H, β), 8.34 (d, $J = 4.8$ Hz, 2H, β), 8.21 (d, $J = 4.8$ Hz, 2H, β), 8.19 (d, $J = 4.8$ Hz, 2H, β), 8.11 (s, 2H, Ar), 8.07 (d, 4H, Ar), 7.91 (s, 2H, Ar), 7.87 (s, 2H, Ar), 7.82 (s, 2H, Ar), 7.79 (s, 2H, Ar), 7.73 (s, 2H, Ar), 7.64 (s, 2H, Ar), 6.87 (dd, $J = 13.0$, 3.9 Hz, 2H, H^c), 3.55 (dd, $J = 3.9$, 10.7 Hz, 2H, H^b), 3.20 (dd, $J = 13.0$, 10.7 Hz, 2H, H^a), 2.43 (s, 3H, NMe), 1.59 (s, 18H, *t*Bu), 1.55 (s, 18H, *t*Bu), 1.54 (s, 18H, *t*Bu), 1.49 (s, 18H, *t*Bu), 1.47 (s, 18H, *t*Bu), and 1.44 (s, 18H, *t*Bu) ppm; HR-ESI-MS $m/z = 1928.0297$, calcd for $C_{127}H_{145}N_9Zn_2 = 1928.0204$ [M]$^+$; UV–vis (CHCl$_3$) $\lambda_{max}(\varepsilon) = 429$ (87,000), 504 (12,0000), 582 (37,000), 633 (59,000), 726 (44,000), and 1053 nm (6000 M^{-1} cm^{-1}).
12. Compound data for **5**. ^{1}H NMR (CDCl$_3$, −20 °C): δ 8.95 (s, 2H, H^h), 8.27 (s, 2H, Ar), 8.25 (d, $J = 4.8$ Hz, 2H, β), 8.18 (s, 2H, Ar), 8.17 (d, $J = 4.8$ Hz, 2H, β), 8.08 (s, 2H, Ar), 8.04 (d, $J = 4.8$ Hz, 2H, β), 7.89 (d, $J = 4.8$ Hz, 2H, β), 7.70 (s, 2H, Ar), 7.66 (s, 2H, Ar), 7.59 (s, 2H, Ar), 7.46 (s, 2H, Ar), 7.33 (s, 2H, Ar), 7.21 (s, 2H, Ar), 6.76 (dd, $J = 9.6$, 4.5 Hz, 2H, H^c), 3.10 (dd, $J = 15.8$, 4.5 Hz, 2H, H^b), 2.84 (dd, $J = 15.8$, 9.6 Hz, 2H, H^a), 2.30 (s, 3H, NMe), 1.59 (s, 18H, *t*Bu), 1.56 (s, 18H, *t*Bu), 1.50 (s, 18H, *t*Bu), 1.36 (s, 18H, *t*Bu), 1.32 (s, 18H, *t*Bu), and 1.30 (s, 18H, *t*Bu) ppm; HR-ESI-MS $m/z = 1915.0391$, calcd for $C_{127}H_{146}N_9Ni_2 = 1915.0420$ [M+H]$^+$; UV–vis (CHCl$_3$) $\lambda_{max}(\varepsilon) = 432$ (93,000), 491 (118,000), 615 (48,000), 726 (54,000), 772 nm (30,000), and 914 nm (2000 M^{-1}cm^{-1}).
13. *Crystallographic data for* **5**. $C_{127}H_{145}N_9Ni_2$, $Mw = 1914.94$, orthorhombic, *Pcam* (No. 57), $a = 17.206(5)$ Å, $b = 17.642(5)$ Å, $c = 41.079(5)$ Å, $V = 12469(9)$ Å^3, $D_c = 1.020$ g/cm^3, $Z = 3$, $R_1 = 0.0748$ ($I > 2.0\sigma(I)$), $wR_2 = 0.2552$ (all data), GOF = 1.083 ($I > 2.0\sigma(I)$). Crystals were grown from slow vapor diffusion of 2-propanol to a CHCl$_3$ solution of **5**. CCDC-677840.
14. (a) Maclean, A. L.; Foran, G. J.; Kennedy, B. J.; Turner, P.; Hambley, T. W. *Aust. J. Chem.* **1996**, *49*, 1273; (b) Jentzen, W.; Unger, E.; Song, X.-Z.; Jia, S.-L.; Turowska-Tyrk, I.; Schweitzer-Stenner, R.; Dreybrodt, W.; Scheidt, W. R.; Schelnutt, J. A. *J. Phys. Chem. A* **1997**, *101*, 5789.
15. Chang, D.; Malinski, T.; Ulman, A.; Kadish, K. M. *Inorg. Chem.* **1984**, *23*, 817.
16. (a) Baran, J.; Mayr, H. *J. Am. Chem. Soc.* **1987**, *109*, 6519; (b) Baran, J.; Mayr, H. *J. Org. Chem.* **1989**, *54*, 5012; (c) Baran, J.; Mayr, H. *J. Org. Chem.* **1989**, *54*, 5774; (d) Giera, H.; Huisgen, R.; Polborn, K. *Eur. J. Org. Chem.* **2005**, *17*, 3781; (e) Huisgen, R.; Giera, H.; Polborn, K. *Tetrahedron* **2005**, *61*, 6143; (f) Pearson, W. H.; Mans, D. M.; Kampf, J. W. *J. Org. Chem.* **2004**, *69*, 1235.