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Metalation Chemistry of *meso*-Aryl-Substituted Expanded Porphyrins

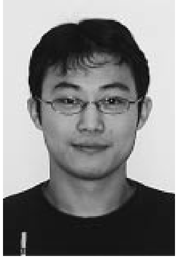
Soji Shimizu[a] and Atsuhiro Osuka*[a]

Keywords: Aromaticity / Conjugation / Macrocyclic ligands / Porphyrinoids

meso-Aryl-substituted expanded porphyrins are structural analogues of *meso*-aryl-substituted porphyrins. They exhibit rich and novel coordination behaviors, including multi-metal chelation due to the large cavities, spin–spin interaction arising from the proximity of metal centers, and large changes in their structural and electrochemical properties upon metalation. The recent discovery of a facile, one-pot synthesis of a series of *meso*-aryl-substituted expanded porphyrins enables us to investigate their metal-complexation chemistry. The aim of this Microreview is to highlight recent progress in the synthesis and characterization of metal complexes of *meso*-aryl-substituted expanded porphyrins.

Introduction

Porphyrins, which play a key role in biological as well as artificial processes, are undoubtedly one of the most widely studied macrocycles and are characterized as 18π-electron aromatic ligands that can accommodate most metal ions to form 1:1 metal complexes.[1] In recent years, porphyrin analogues that include modified, confused, contracted, and expanded ones have attracted increasing attention owing to their intriguing properties, which are very difficult or impossible to achieve in porphyrins. Among these, expanded porphyrins bearing more than four pyrrole rings have been demonstrated to be quite promising due to their larger conjugation and diversity that allow remarkable absorption spectra ranging from the UV/visible to the near-IR region, variable oxidation states that are interconvertible among aromatic, antiaromatic, and nonaromatic systems, and multi-metal coordinating behaviors.[2–7] On account of these promising properties, they are in the spotlight in various fields, including receptors for anions,[8] ligands for several transition and lanthanoid metal ions, sensitizers for photodynamic therapy (PDT),[5,9] and magnetic resonance imaging (MRI) contrast agents.[10] In addition, they have re-



Soji Shimizu was born in 1979 in Kyoto, Japan. He received his BSc and MSc degrees in 2002 and 2004, respectively, from Kyoto University. He is currently a PhD student with Professor Osuka at the same university, focusing on the synthesis and exploration of expanded porphyrins. During spring 2005, as a visiting fellow, he stayed at Professor Jonathan L. Sessler's laboratory in the Department of Chemistry and Biochemistry, the University of Texas at Austin. He was selected as a Research Fellow of the Japan Society for the Promotion of Science (JSPS) in 2004.

Atsuhiro Osuka was born in Gamagori, Aichi, in 1954. He received his PhD degree from Kyoto University in 1982 on the photochemistry of epoxyquinones. In 1979, he started his academic career at the Department of Chemistry, Ehime University as an assistant professor. In 1984, he moved to the Department of Chemistry, Kyoto University, where he became a professor of chemistry in 1996. He was awarded the CSJS Award for Young Chemists in 1988 and the Japanese Photochemistry Association Award in 1999. His research interests cover many aspects of synthetic approaches toward the artificial photosynthesis and development of porphyrin-related compounds with novel structures and functions. He was selected as a project leader of Core Research for Evolutional Science and Technology (CREST) of JST.

MICROREVIEWS: This feature introduces the readers to the authors' research through a concise overview of the selected topic. Reference to important work from others in the field is included.

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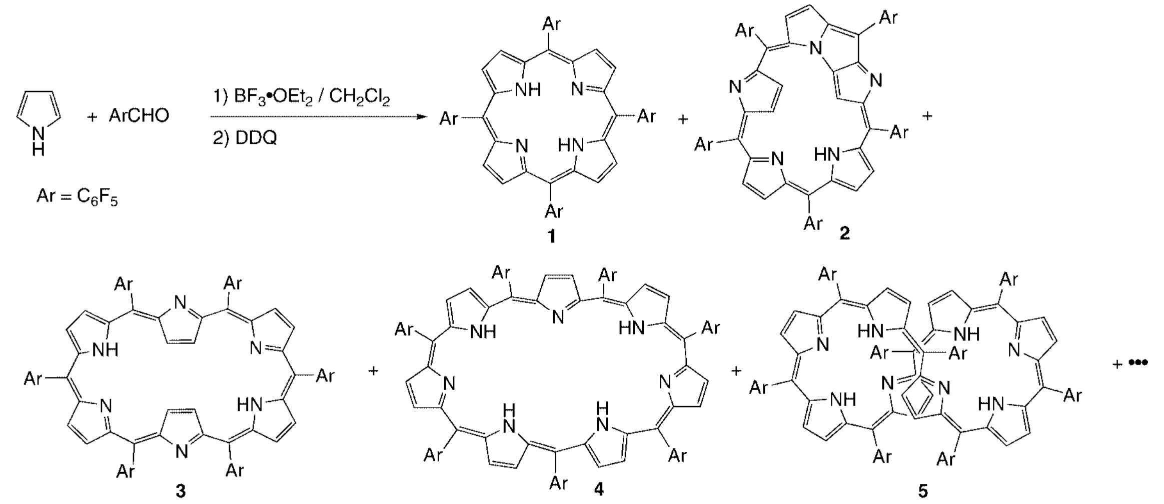
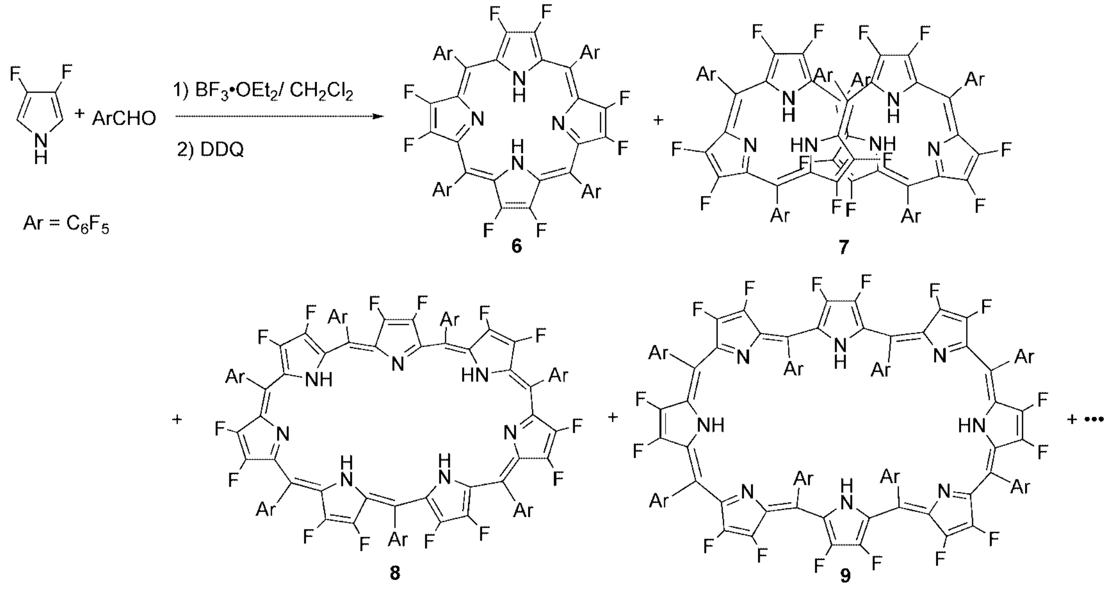
[a] Department of Chemistry, Graduate School of Science, Kyoto University, and Core Research for Evolutional Science and Technology (CREST), Japan Science and Technology Agency, Sakyo-ku, Kyoto 606-8502, Japan
Fax: +81-75-753-3970
E-mail: osuka@kuchem.kyoto-u.ac.jp

cently been shown to have potential as nonlinear optical materials owing to their large two-photon absorption (TPA) cross-sections, which will lead to a broad range of applications such as three-dimensional microfabrication, optical data storage, and optical limiting.[11,12] These promising attributes have encouraged diverse synthetic efforts towards various expanded porphyrins that differ in ring size, ring connectivity, peripheral substituents, and core modification.[5,13–21] Recently, we found that a modified Rothemund–Lindsey porphyrin synthesis leads to the formation of a series of *meso*-aryl-substituted expanded porphyrins that are all real porphyrin homologues in terms of a regularly alternating pyrrole and methine carbon arrangement (Scheme 1).[22] This synthesis requires aryl aldehyde substrates bearing electron-deficient and bulky substituents both at the 2- and 6-positions and 10 times higher concentrations of substrates (ca. 67 mM) than those optimized for the porphyrin synthesis. A series of fully fluorinated expanded porphyrins was prepared in a similar manner from the reaction of 3,4-difluoropyrrole and pentafluorobenzaldehyde (Scheme 2).[23] The ring-size-selective synthesis of expanded porphyrins has been achieved by using dipyrromethane and tripyrromethane as starting substrates under milder reaction conditions (Scheme 3).[24] This ring-size-selective synthesis has also allowed the preparation of hexaphyrins and octaphyrins bearing electron-rich *meso*-aryl substituents.[25]

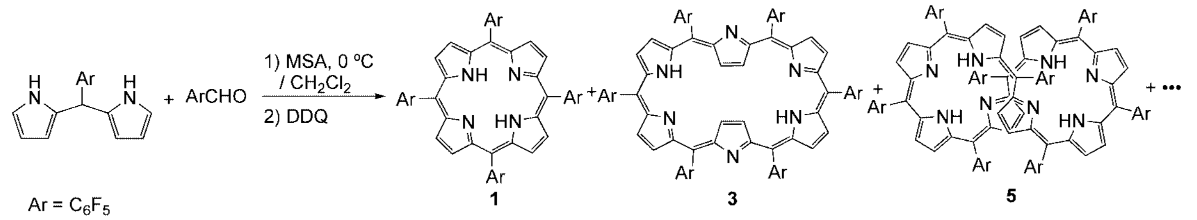
The metalation chemistry of expanded porphyrins can be traced back to the 1980s. Representative examples are summarized in Figure 1. In 1983, Gossauer et al. reported the preparation of β-dodecaalkyl-substituted [26]hexaphyrins, which were converted into their bis-Zn^{II} and bis-Pd^{II} complexes.[26] Vogel and co-workers have synthesized a series of β-alkyl-substituted octaphyrins bearing twisted fig-



Scheme 1. Synthesis of *meso*-aryl-substituted expanded porphyrins.



Scheme 2. Synthesis of perfluorinated expanded porphyrins.



Scheme 3. Ring-size selective synthesis.

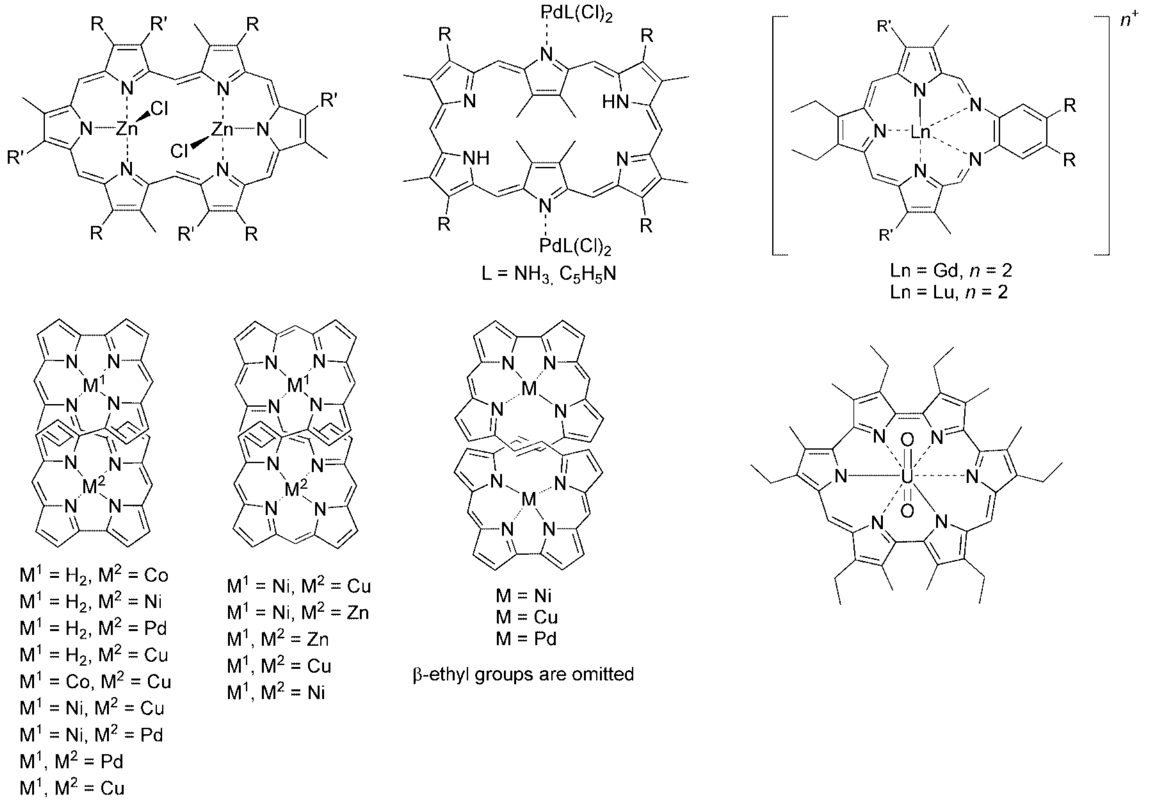


Figure 1. Representative examples of metal complexes of expanded porphyrins.

ure-eight conformations and revealed their facile complexation behaviors with several transition metal ions.[27] The figure-eight conformations were fixed upon complexation, which enabled optical separation of the metalated octaphyrins for the first time.[27a] Sessler et al. have investigated lanthanoid metal complexes of texaphyrins and medicinal applications of gadolinium texaphyrins as sensitizers for photodynamic therapy.[5,9] They synthesized the bis-Cu^{II} complex of amethyrin and revealed the proximity of the metal centers and their antiferromagnetic behavior.[28] Recently, they have investigated the usage of expanded porphyrins as a colorimetric actinoid sensor.[29] Thus, expanded porphyrins are becoming increasingly important platforms for several metal ions and as promising materials in various fields. From this point of view, the *meso*-aryl-substituted expanded porphyrins can be regarded as another promising candidate to explore novel functional metal complexes since this facile, one-pot reaction affords a series of expanded porphyrins that differ in the number of the constituting pyrrolic subunits and thus in cavity size, conformational flexibility, and stable conformation.

In this Microreview we summarize our own contributions in the synthesis, characterization, and properties of metal complexes of *meso*-aryl-substituted expanded porphyrins, which are presented in order of their ring size. The compound names appearing in this review are partly based on a nomenclature put forward by Franck and Nonn for porphyrinic system.[30] The number in square brackets corresponds to the number of π-electrons in the shortest conjugation pathway and the core name represents the number of pyrroles.

N-Fused Pentaphyrin (NFP_5)

Structures and Properties of the Free Bases

meso-Pentafluorophenyl-substituted pentaphyrin was obtained as its N-fused form, whicht was found to exist as a mixture of two oxidation states {[22]N-fused pentaphyrin ([22]NFP$_5$, **2a**) and [24]NFP$_5$ (**2b**); Figure 2} from the reaction shown in Scheme 1.[22,31] The yield of each compound varied depending on the oxidation time. Thus, **2a** was obtained after oxidation with an excess amount of DDQ for a long time (>15 h) in 18% yield as the sole pentapyrrolic product (Scheme 1).[31b] Alternatively, **2a** was prepared in 28% yield by an acid-catalyzed [3+2] condensation of tripyrrane and dipyrromethane (Scheme 4). Compound **2a** is easily reduced to **2b** with NaBH$_4$, which is quantitatively oxidized back to the original **2a** upon treatment with DDQ (Figure 2). An aromatic ring current effect arising from the 22π-electron conjugation is observed in the ^{1}H NMR spectrum of **2a**, while **2b** shows antiaromatic character due to its 24π-electron conjugation. According to X-ray diffraction analyses, both **2a** and **2b** possess a fused tripentacyclic ring (pyrroles A and B in Figure 3), an outward-pointing pyrrole ring (pyrrole C), and an inward-oriented dipyrromethene moiety (pyrroles D and E). The inverted pyrrole C is significantly tilted for each compound. Except for pyrrole C the entire structure of **2a** is planar, while that of **2b** is severely distorted.

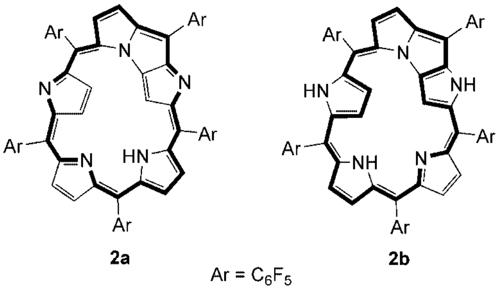
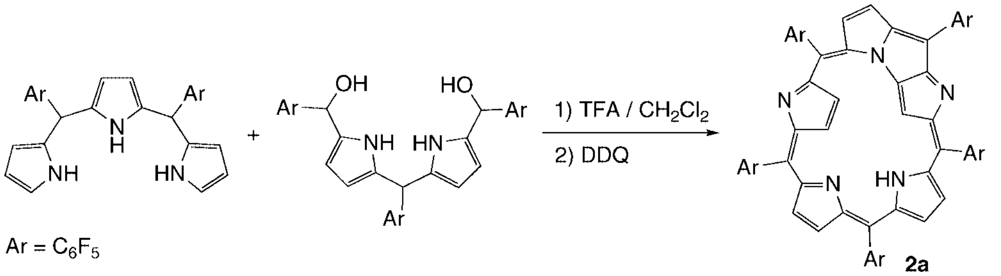


Figure 2. Redox behavior of NFP$_5$.

Metal Complexes of NFP$_5$

Since both **2a** and **2b** possess a dipyrromethene moiety, we investigated complexation of Rh$^{\text{I}}$, which is known, in the coordination chemistry of porphyrinoids, to bind to one dipyrromethene ligand and two carbonyl ligands in a



Scheme 4. Synthesis of **2a** by a [3+2] condensation reaction.

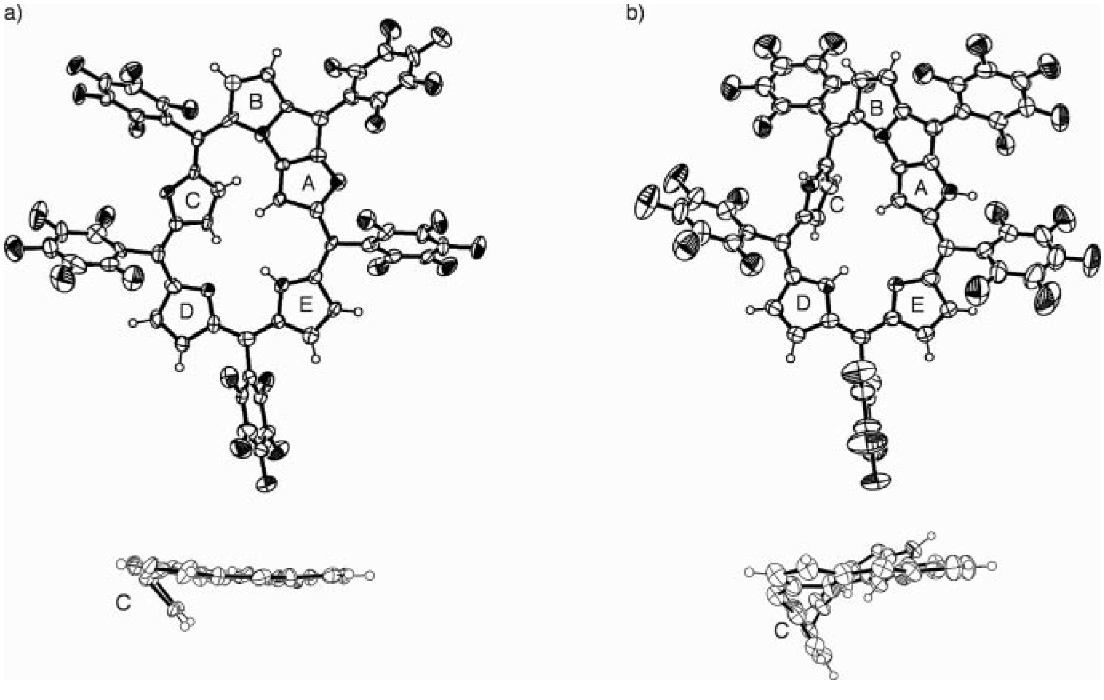


Figure 3. X-ray crystal structures of a) **2a** (preliminary) and b) **2b**; top views (top) and side views (bottom). *meso*-Aryl substituents have been omitted for clarity in the side views.

square-planar fashion.[32–34] Two rhodium complexes **10** and **11** were isolated in 2.4% and 23% yields, respectively, from the metalation of **2a** with two equivalents of $[RhCl(CO)_2]_2$ in CH_2Cl_2 in the presence of sodium acetate at room temperature for 4 h (Figure 4).[31b] The product ratio of **11** to **10** decreased as the reaction time increased. Under refluxing conditions the yield of **10** (42%) was distinctly higher than that of **11** (18%). These results suggest that **10** is the thermodynamic product of this reaction. On the contrary, the complexation of **2b** with $[RhCl(CO)_2]_2$ gave complex **11** as the sole product in 60% yield at room temperature after 1 h.

In the crystal structures, both **10** and **11** preserve basic NFP_5 skeletons with a 22π- and 24π-electron conjugation, respectively, in which the Rh^I ion is bound above the center of the cavity by the dipyrromethene unit (pyrroles D and E for **10** and pyrroles C and D for **11**), with N–Rh distances of around 2.1 Å, and two carbonyl ligands in a square-planar fashion (Figure 5). The entire structure of **10** is relatively planar except for the pyrrole C. On the other hand, **11** has a severely distorted bent conformation despite the fully conjugated system. In accordance with these results, the ^1H NMR spectrum of **10** displays peaks for the inner β-CH protons of pyrroles A and C as a singlet at δ = 0.05 ppm and as a pair of doublets at δ = 1.62 and 1.16 ppm, respectively, and the outer β-CH protons as three pairs of doublets at δ = 9.23, 9.21, 8.61, 8.29, 8.21, and 8.13 ppm that indicate a diatropic ring-current effect arising from the planar structure and 22π-electron conjugation. In the ^1H NMR spectrum of **11**, however, resonances due to the inner and outer NH protons of pyrroles E and A are observed at δ = 0.68 and 9.44 ppm, respectively, indicating, to our surprise, a substantial diatropic ring current for **11**, which is also supported by the up- and downfield shifts of the peaks due to the inner and outer β-CH protons, respectively.

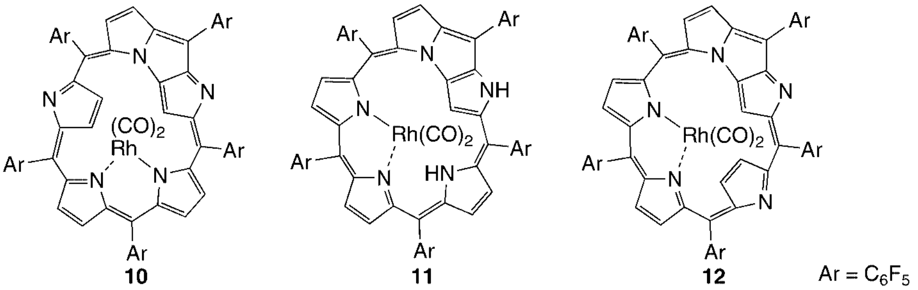


Figure 4. Rh^I complexes of NFP_5.

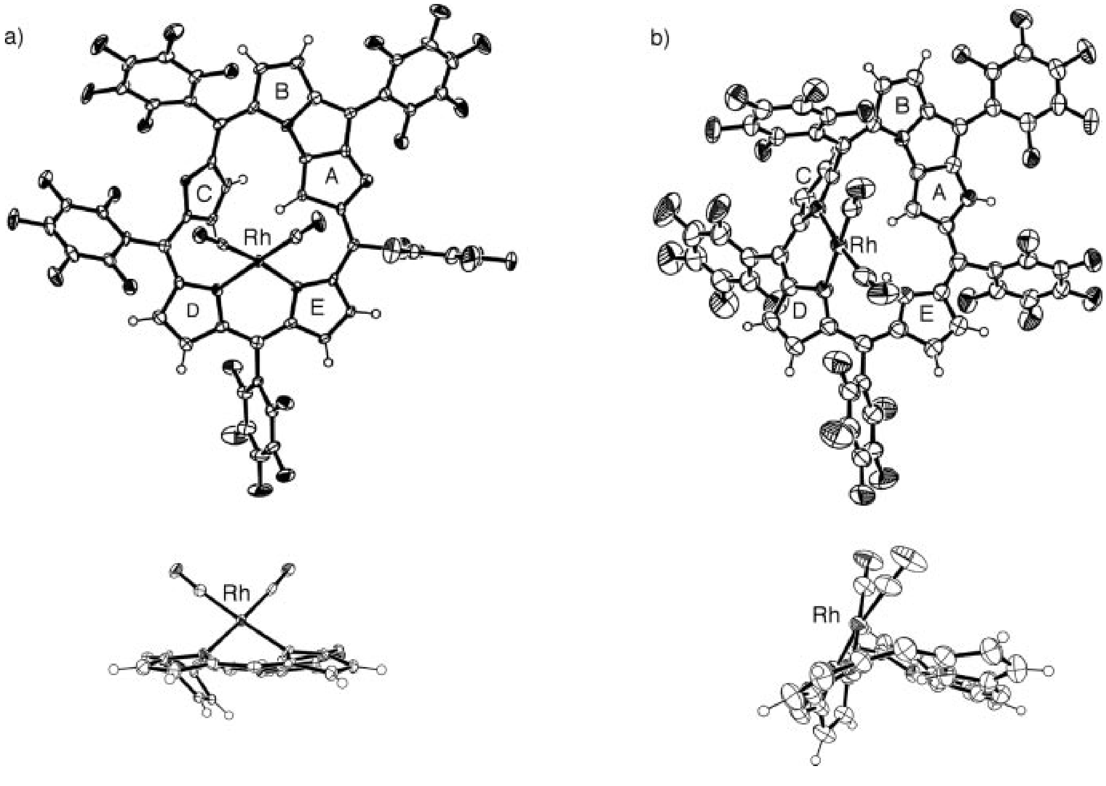


Figure 5. X-ray crystal structures of a) **10** and b) **11**; top views (top) and side views (bottom). *meso*-Aryl substituents have been omitted for clarity in the side views.

Since complex **10** is the major product at high temperature, thermal conversion of **11** to **10** was examined in refluxing CH_2Cl_2; this reaction turned out to be unsuccessful. Considering that the number of conjugated π electrons is 22 for **10** and 24 for **11**, interconversion between these complexes by two-electron oxidation and reduction should be feasible. Thus, treatment of **11** with DDQ at room temperature quantitatively converted it into complex **10** by a novel pivot-like-walk rearrangement of Rh. The details of this process were monitored by ^1H NMR spectroscopy, in which an intermediate **12** (Figure 4) was detected before the final formation of **10**. In contrast, reduction of **10** with $NaBH_4$ caused demetalation to give **2b** without producing **11**.

Hexaphyrin

Structures and Properties of the Free Bases

Hexaphyrin **3**, which was first synthesized by Cavaleiro and co-workers,[35] was one of the major products from the modified Rothemund–Lindsey reaction and was obtained in 16–20% yield as an oxidized form with 26π electrons in its conjugation (Scheme 1).[22] The yield was improved by using the ring-size selective synthesis.[24] Upon treatment with $NaBH_4$, [26]hexaphyrin (**3a**) was easily reduced to [28]hexaphyrin (**3b**), which could be quantitatively oxidized back to the original [26]hexaphyrin (Figure 6). In the solid, **3a** exhibits a planar rectangular structure with two inverted pyrrole rings (Figure 7, a).[35] Although a structural analysis of **3b** unfortunately has not yet been successful, the structure of an analogue of **3b** bearing alkylamino substituents at the *p* position of the pentafluorophenyl groups and exhibiting almost identical UV/Vis and NMR spectra to **3b** was revealed crystallographically to possess a similar conformation to that of **3a**.[36] In solution, **3a** exhibits aromatic character due to the 26π-electron conjugation and planar conformation. On the other hand, the ^1H NMR spectrum of **3b** indicates aromatic rather than antiaromatic character. The explanation for this is uncertain at this stage.

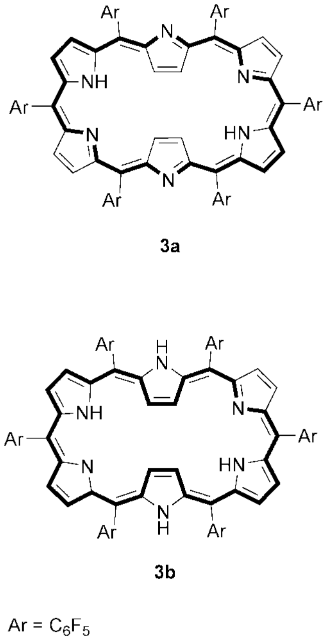


Figure 6. Redox behavior of hexaphyrin.

We have also investigated the synthesis of hexaphyrins bearing several substituents not only at the *meso* position but also at the β position. Perfluorinated [28]hexaphyrin (**7**) was isolated in 2–5% yield from a mixture of other perfluorinated expanded porphyrins obtained from the reaction of 3,4-difluoropyrrole with pentafluorobenzaldehyde.[23] In the solid state, **7** takes a figure-eight conformation and hence exhibits nonaromatic character (Figure 7, b). In addition to the coordination properties of these hexaphyrins, they are also drawing much attention as a near-IR absorbing dye.

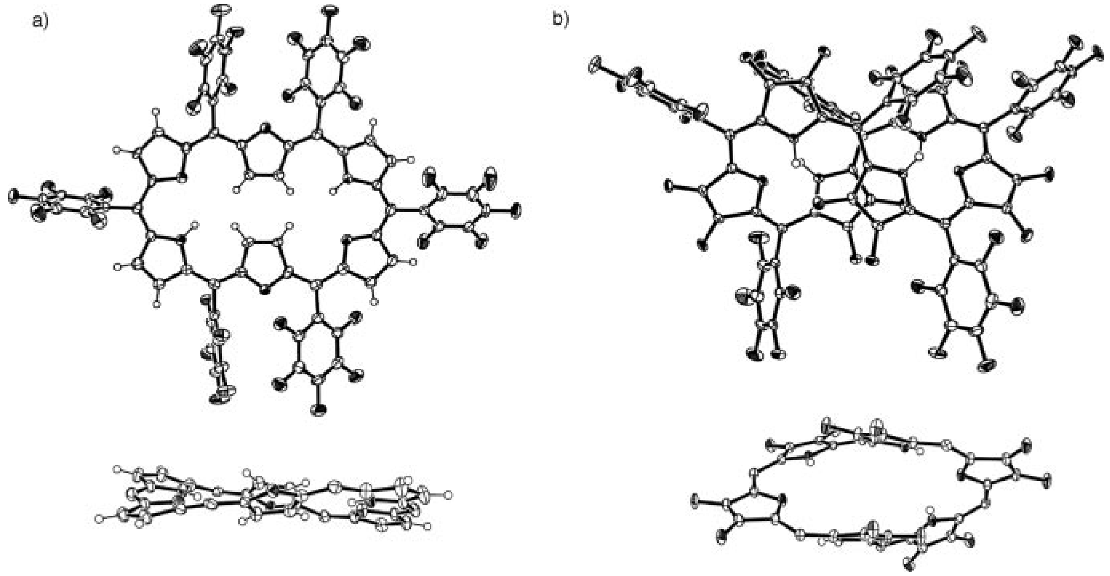


Figure 7. X-ray crystal structures of a) **3a** and b) **7**; top views (top) and side views (bottom). *meso*-Aryl substituents have been omitted for clarity in the side views.

The absorption spectrum of **3a** shows a Soret-like band at 568 nm and Q-like absorptions at 712, 898, and 1026 nm, and is formally similar to that of porphyrin although with substantial red-shifts owing to the extension of the π-conjugation.[11,35] Compound **3a** exhibits fluorescence emission at 1036 nm with a weak vibronic band at 1205 nm.[11] Recently, molecules having large two-photon absorption (TPA) cross-sections [$\sigma^{(2)}$] have been of great interest due to their potential applications in a variety of fields described in the previous section. Aromatic **3a** exhibits a large TPA cross-section value of about 10^4 GM, which makes it quite attractive for further applications.[11]

Copper Complexes of Hexaphyrins

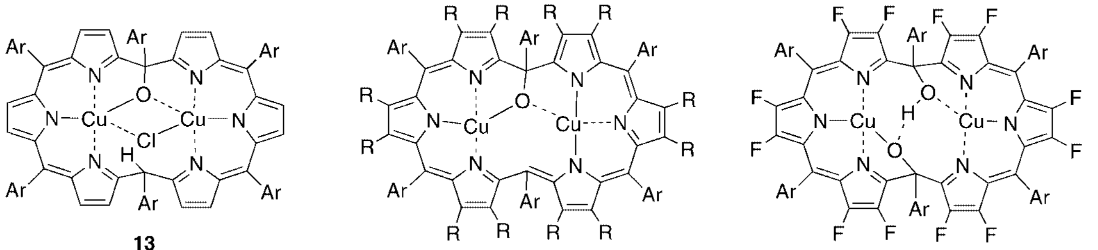
The complexation reaction of **3a** with anhydrous $CuCl_2$ and NaOAc in CH_2Cl_2 gave the dicopper complex **13** in 84% yield.[37] Interestingly, metalation in the presence of anhydrous $Cu(OAc)_2$ and NaOAc led to isolation of a different dicopper complex **14** in 90% yield (Figure 8). Both structures were elucidated by X-ray single crystal analysis. The structure of **13** takes a gable structure with two semiplanar tripyrrolic planes in which each copper ion is bound to the bridging chloride atom, the oxygen atom attached at the *meso* position, and three nitrogen atoms of the tripyrrolic unit, in a square-pyramidal fashion (Figure 9, a). Compound **14** exhibits a similar gable structure with two copper ions, which are each bound to the *meso*-attached oxygen atom and three pyrrolic nitrogen atoms in a square-planar fashion (Figure 9, b). Contrary to complex **13**, there is no axial bridging in **14**.

Similar copper metalation was tested for perfluorinated [28]hexaphyrin (**7**). Complex **15** was obtained as the sole product (96% yield) from the reaction with $CuCl_2$, while metalation with $Cu(OAc)_2$ afforded a mixture of complex **15** and **16** in 26 and 56% yields, respectively (Figure 8). The structure of **15** is quite similar to that of **14**, while **16** takes a different structure in which the two copper ions are not directly bridged but are coordinated separately by the different tripyrrolic ligand and *meso*-attached oxygen atom (Figures 9, c and d). The oxygen ligands in **16** are from a tertiary alcohol and an alkoxide. Importantly, this structure leads to the assignment of **16** as a mixed-valence Cu^I/Cu^{II} complex. The proximity of the two Cu^{II} ions in **13**, **14**, and **15** allows antiferromagnetic couplings with exchange interaction values (J) of –8.27, –87.6, and –42.1 cm^{-1}, respectively. On the contrary, complex **16** has a temperature-independent χ_pT value (0.4229 emu K mol^{-1}) corresponding to an $S = 1/2$ state, in agreement with the Cu^I/Cu^{II} mixed-valence state.

Doubly N-confused [26]Hexaphyrin from [26]Hexaphyrin

In the course of their extensive investigations on N-confused porphyrinoids,[38] Furuta et al. have reported the synthesis of a doubly N-confused hexaphyrin (DNCH, **17**) bearing two oxygenated confused pyrrole rings, which offer efficient coordination sites for two transition metal ions such as Cu^{II} **18** and Ni^{II} **19** (Figure 10).[38c] Compound **17** and its bis-metal complexes are also attractive as near-IR-absorbing dyes due to their expanded π-electronic system but have been rather poorly explored, mainly due to the tedious, multi-step synthesis of the N-confused tripyrrane precursor.[38d] During our exploration of the metalation chemistry of hexaphyrin **3a**, we serendipitously found that treatment with Cu^I under aerobic conditions in pyridine efficiently provided the bis-Cu^{II} complex of DNCH (**18**; 24.4% yield), whose structure was confirmed by X-ray analysis (Figure 11, a).[39] Remarkably, both the inverted pyrrole rings of **3a** undergo simultaneous rearrangements to form N-confused pyrroles with concomitant oxygenation at the internal pyrrolic α positions. Although the reaction mechanism has not been elucidated yet, we anticipate the involvement of CuCl–pyridine–O_2 oxidation in this reaction on the basis of several experimental facts.

The bound copper ions are easily demetalated upon treatment with TFA in CH_2Cl_2 to give the free base **17**, which is a good ligand system for two divalent or trivalent metal ions (Cu^{II} **18**, Ni^{II} **19**, Co^{II} **20**, Zn^{II} **21**, Mn^{III} **22**, and Fe^{III} **23**; Figure 10). The ^1H NMR spectra of **17** and **21** display strong diatropic ring currents in line with their 26π aromatic conjugation. The absorption spectrum of **17** exhibits a Soret-like band at 566 nm with a shoulder at 586 nm and Q-like bands at 722, 793, 911, and 1047 nm. Interestingly, **17** shows fluorescence at 1058 nm, with a vibronic structure that has a very small Stokes shift. These observations suggest a rigid structure supported by multiple intramolecular hydrogen-bonding interactions.



13

14: R = H
15: R = F

16

Ar = C_6F_5

Figure 8. Bis-Cu complexes of hexaphyrins.

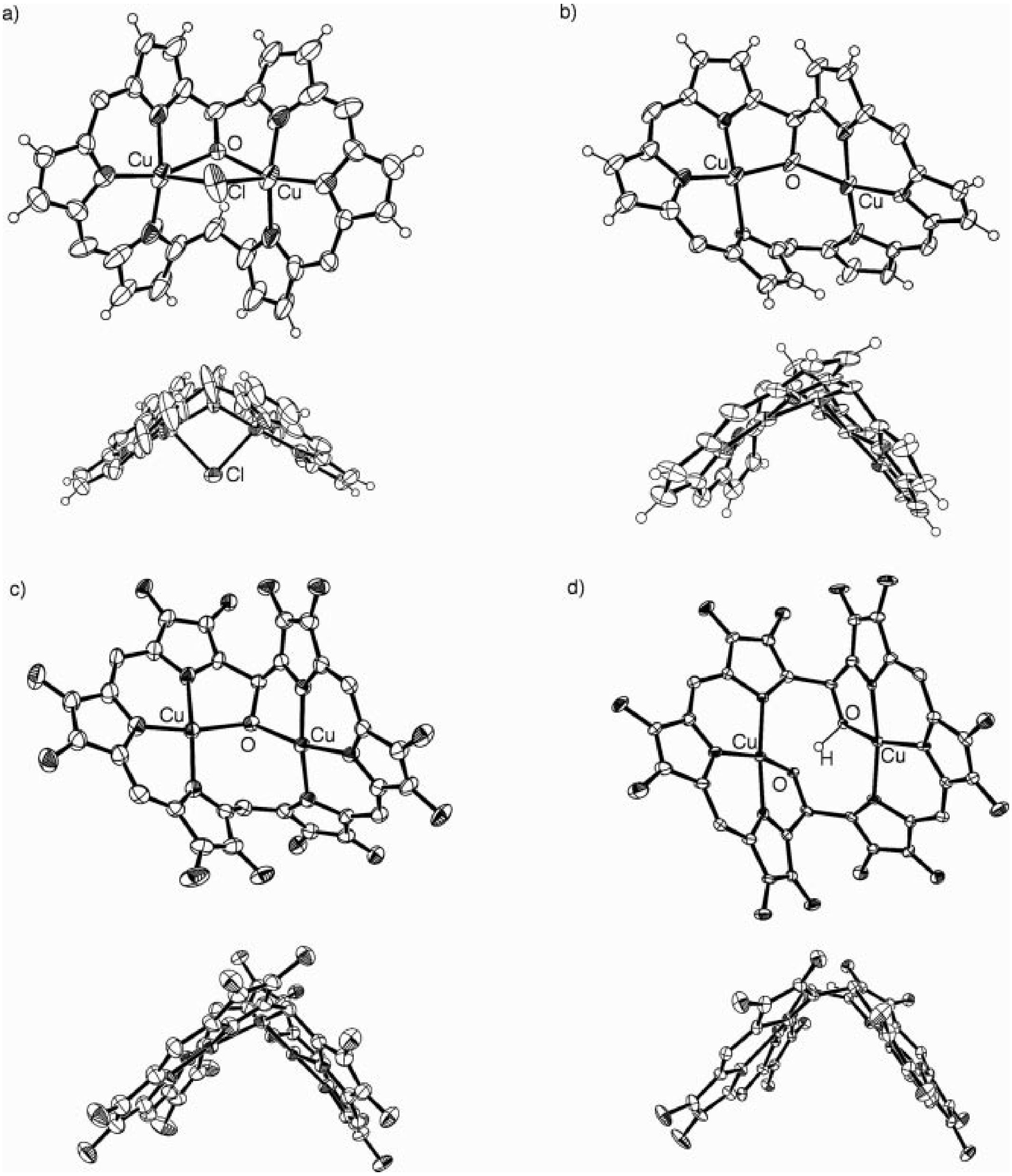
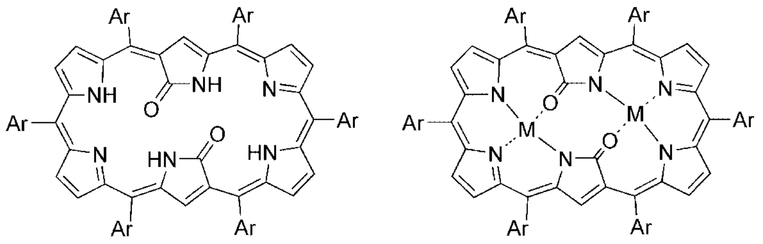


Figure 9. X-ray crystal structures of a) **13**, b) **14**, c) **15**, and d) **16**; top views (top) and side views (bottom). *meso*-Aryl substituents have been omitted for clarity.



17

Ar = C_6F_5

18: M = Cu
19: M = Ni
20: M = Co
21: M = Zn
22: M = MnCl
23: M = FeCl

Figure 10. Doubly N-confused hexaphyrin and its metal complexes.

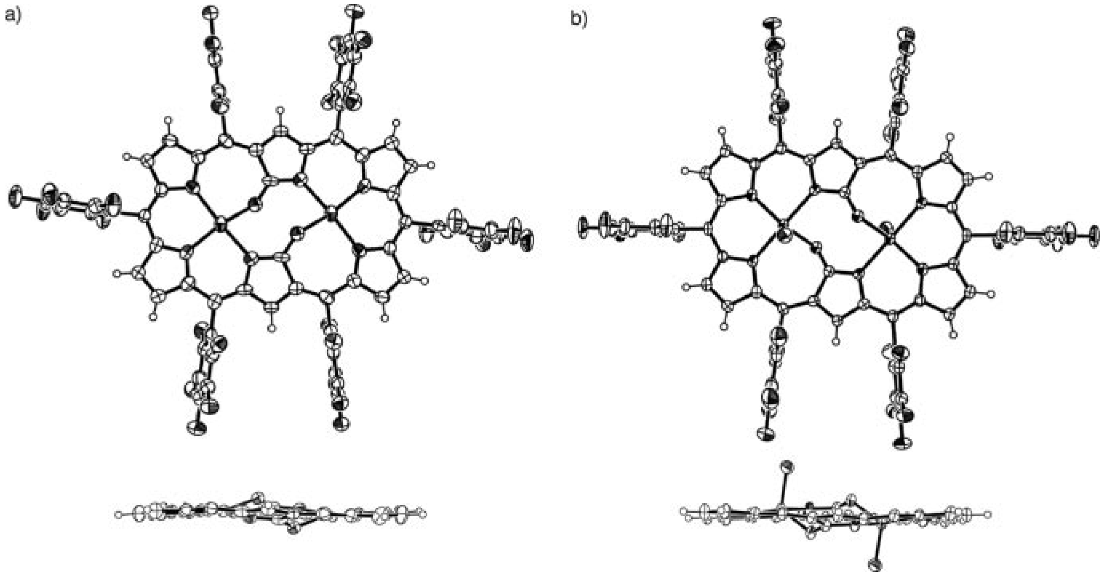
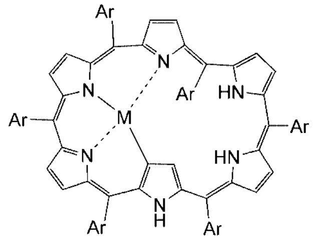


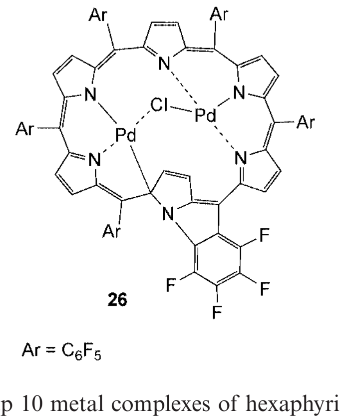
Figure 11. X-ray crystal structures of a) **18** and b) **20**; top views (top) and side views (bottom). *meso*-Aryl substituents have been omitted for clarity in the side views. Water molecules each coordinate to the axial position of the cobalt ion in **20**.

Group 10 Metal Complexes of Hexaphyrin

The copper complexes described above exhibit large structural changes upon metalation. Next, we investigated the complexation of hexaphyrin with group 10 metal ions such as Ni^{II}, Pd^{II}, and Pt^{II}.[40] When a toluene solution of **3a** and $Ni(acac)_2$ was refluxed for one hour in the presence of sodium acetate under anaerobic conditions the mono-Ni^{II} complex **24** was obtained in 50% yield. Similarly, the mono-Pt^{II} complex **27** was obtained in 56% yield from the reaction of **3a** with $PtCl_2$ and NaOAc in refluxing CH_2Cl_2 under argon. Curiously, however, metalation with $PdCl_2$ in refluxing CH_2Cl_2 in the presence of NaOAc provided a mixture of mono-Pd^{II} (**25**) and bis-Pd^{II} (**26**) complexes, which were isolated in 50 and 9% yields, respectively (Figure 12). Single crystal analyses revealed that complexes **24**, **25**, and **27** possess a metal–carbon bond and have distorted structures (Figures 13, a–c). The ^{1}H NMR spectra of **24**, **25**, and **27** show nonaromatic character due to the nonplanar structures. In the crystal structure of **26** the two Pd^{II} ions are bridged by the chloride atom. One Pd^{II} ion is bound to three pyrrolic nitrogen atoms and the other is bound to two pyrrolic nitrogen atoms and a pyrrolic α-carbon, and an N-fusion reaction of the pyrrole E and the adjacent pentafluorophenyl group has taken place to form a planar pentacyclic ring (Figure 13, d). Thus, the internal β-pyrrolic CH bond of **3a** is activated to form a metal–carbon bond in the metalation reactions with group 10 metal ions.



24: M = Ni
25: M = Pd
27: M = Pt



26

Ar = C_6F_5

Figure 12. Group 10 metal complexes of hexaphyrin.

Gold Complexes of Hexaphyrin

Metal complexes of hexaphyrin preserving the original planar and rectangular shape are of great interest from the viewpoint of regulation of aromaticity and antiaromaticity. Towards this goal, metal ions with a strong C–H activation ability would be promising. During the exploration of the complexation chemistry of hexaphyrins, we fortunately found that gold metalation of **3a** accomplished this goal to provide mono-Au^{III} and bis-Au^{III} complexes.[41] A solution of **3a** and $NaAuCl_4$ in a 4:1 mixture of CH_2Cl_2 and methanol was stirred in the presence of sodium acetate at room temperature for three days. Separation on a silica gel column provided the mono-Au^{III} (**28**) and bis-Au^{III} (**29**) complexes in 16 and 14% yield, respectively, along with 15% of

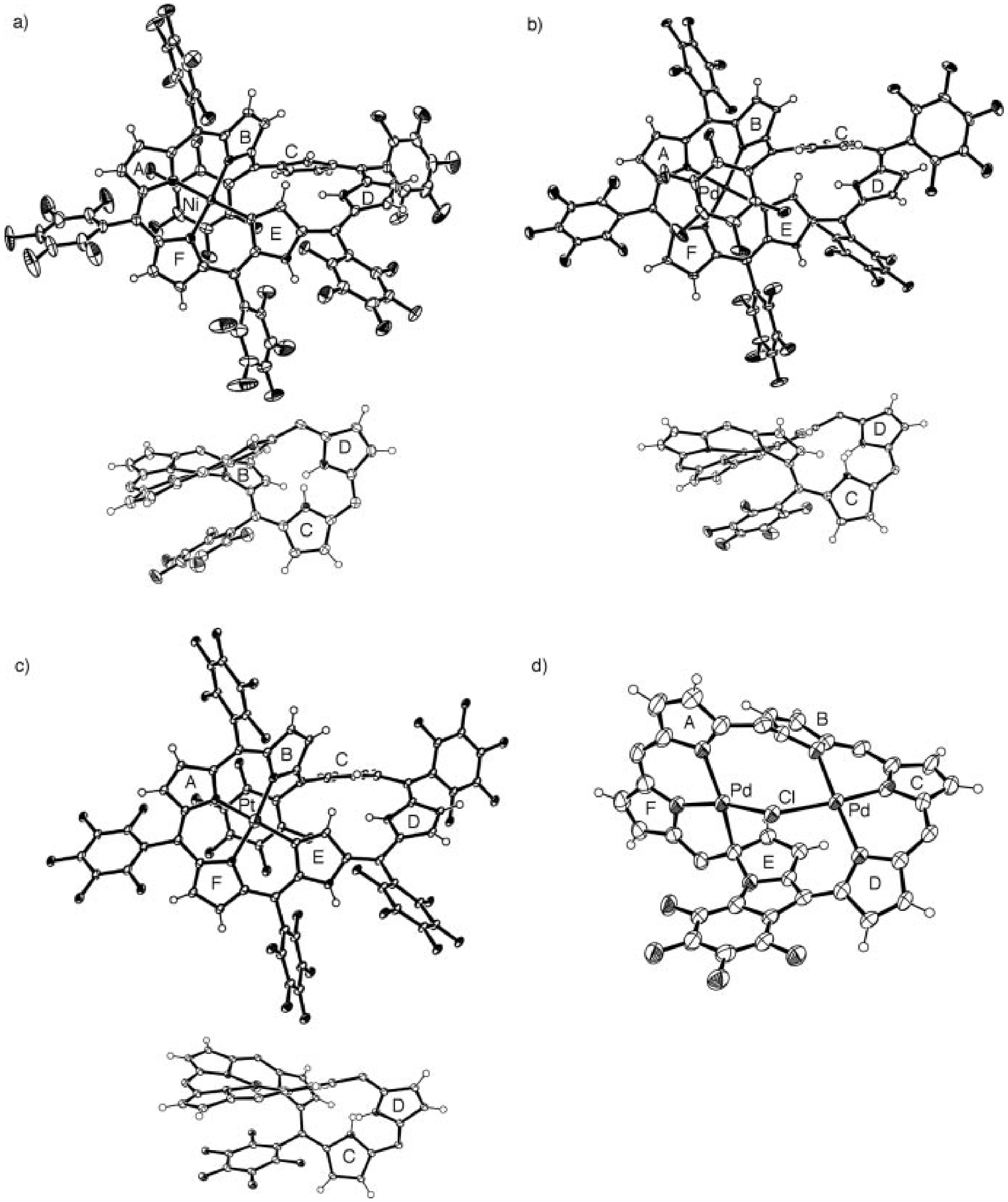


Figure 13. X-ray crystal structures of a) **24**, b) **25**, c) **27** (preliminary), and d) **26**; top views (top) and side views (bottom). *meso*-Aryl substituents have been partially omitted for clarity.

recovered **3a** (Figure 14). Curiously, in both crystal structures the inner β-CHs have been activated to form Au–C bonds and the Au^{III} ions are coordinated to two pyrrolic nitrogen atoms and two pyrrolic β-carbon atoms within a flat [26]hexaphyrin core. The structure of **28** is planar in the coordinated moiety and rather distorted in the cavity, while **29** has a much more planar but overall bent structure (Figure 15). These structural differences can be explained by the steric congestion between the inner pyrrolic β-CHs. As anticipated from their crystal structures, aromaticity of these complexes was observed in their ^{1}H NMR spectra. The outer β-CH protons of **28** appear downfield at δ = 9.51, 9.36, 9.35, and 9.03 ppm, and the inner β-CH and NH protons are seen at δ = –2.93 and –2.08 ppm, respectively, while for **29** the outer β-CH protons appear at δ = 9.66 and 9.51 ppm (Figures 16, a and b). Rigidification by Au coordination has been revealed to play a very important role in enhancing aromatic character, which, in turn, suggests a possible attainment of antiaromatic [28]hexaphyrin in the planar frame. Thus, complexes **28** and **29** were reduced with $NaBH_4$ to give complexes **30** and **31** without demetalation (Figure 14). The structures of **30** and **31** were both preliminarily revealed by X-ray analyses to keep the original rectangular structures but to have two NH hydrogen atoms at

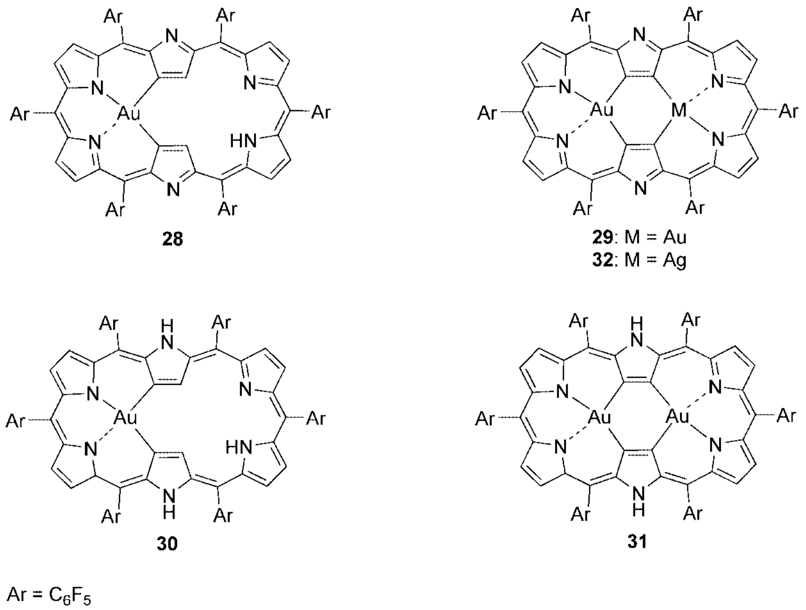


Figure 14. Gold complexes of hexaphyrin.

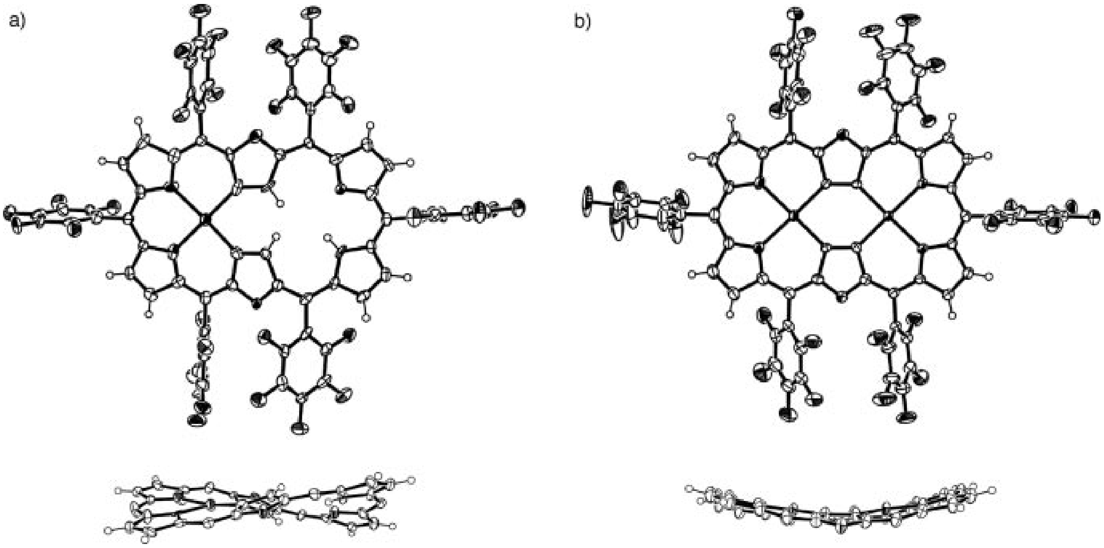


Figure 15. X-ray crystal structures of a) **28** and b) **29**; top views (top) and side views (bottom). *meso*-Aryl substituents have been omitted for clarity in the side views.

the inverted pyrroles. Very curiously, and consistent with Hückel's rule, the ^{1}H NMR spectra of **30** and **31** show a paratropic ring-current effect (Figures 16, c and d). In the ^{1}H NMR spectrum of **30**, the inner β-CH and NH protons are observed at δ = 19.39 and 24.57 ppm, respectively, while the outer β-CH protons appear as four doublets at δ = 5.02, 4.92, 4.32, and 4.07 ppm and the outer NH protons appear at δ = 4.10 ppm. Similarly, the ^{1}H NMR spectrum of **31** exhibits the outer β-CH protons as a pair of doublets at δ = 3.16 and 3.10 ppm and the outer NH protons as a broad singlet at δ = 1.81 ppm. Considering the nonaromaticity of the group 10 metal complexes **24**, **25**, and **27**, firm rigidification of the planar conformation causes the strong antiaromatic character in [28]hexaphyrin.

Complex **28** still has a vacant cavity that may allow coordination of another metal ion. This possibility was examined by treating **28** with CF_3COOAg to give the Au^{III}/Ag^{III} hetero complex **32** in 58% yield with concomitant oxidation of Ag^{I} to Ag^{III} in order to fit into the core.

Octaphyrin

Structures and Properties of the Free Bases

Due to its large conjugation, *meso*-aryl-substituted octaphyrin is supposed to possess three different redox states with 34π-, 36π-, and 38π-electrons (**5b**, **5a**, and **5c**, respectively, in Figure 17). From the reaction shown in Scheme 1, octaphyrin was obtained as [36]octaphyrin (**5a**) in 5–6% yield. The yield of **5a** was improved by using the ring-size selective synthesis.[24] In the crystal structure, **5a** takes a twisted figure-eight conformation in which there are two

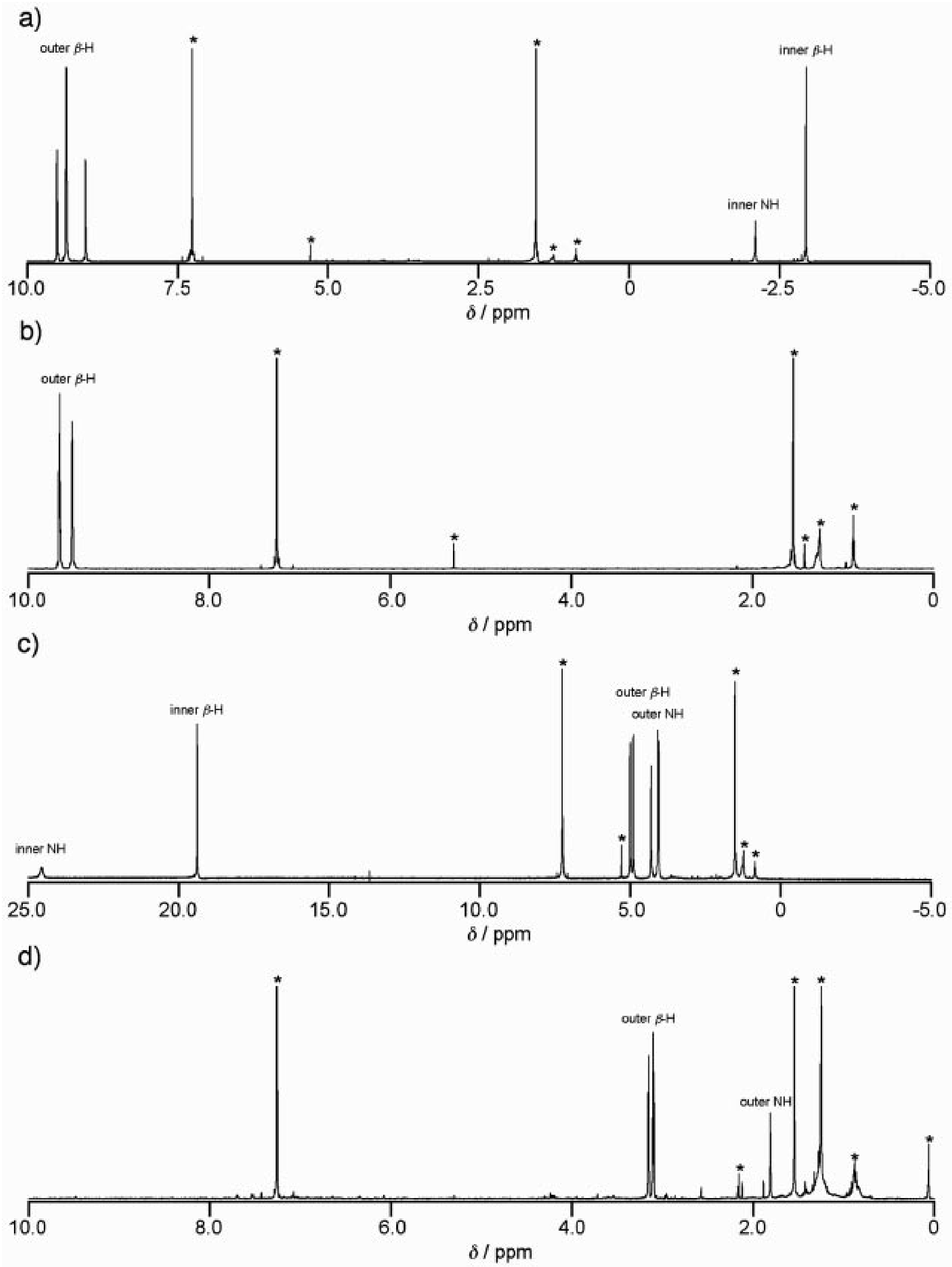


Figure 16. ^{1}H NMR spectra of a) **28**, b) **29**, c) **30**, and d) **31** in CDCl$_3$. * indicates solvent and solvent impurities.

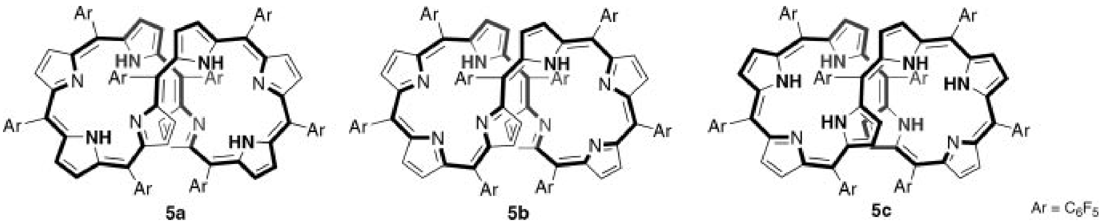


Figure 17. Redox behaviors of octaphyrin.

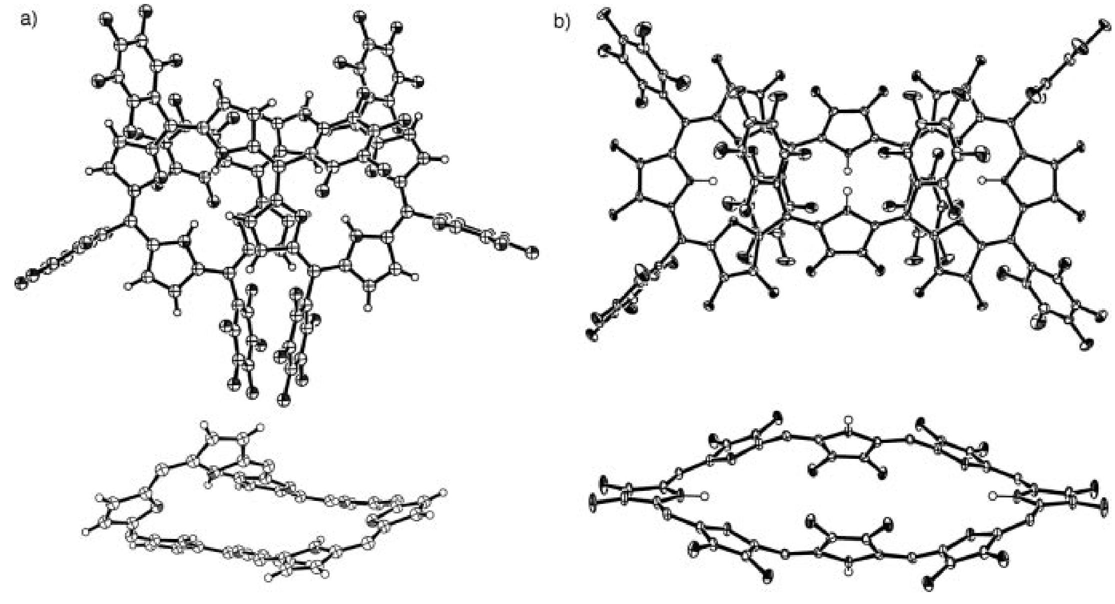


Figure 18. X-ray structures of a) **5a** and b) **9**; top views (top), and side views (bottom). *meso*-Aryl substituents have been omitted for clarity in the side views.

porphyrin-like teterapyrrolic hemimacrocycles; it thus has the potential to coordinate one metal ion in each cavity (Figure 18, a).[22] Upon reduction with $NaBH_4$, **5a** is quantitatively converted into [38]octaphyrin (**5c**), while oxidation of **5a** with MnO_2 gives [34]octaphyrin **5b**. Unfortunately, however, the structures of [34]- and [38]octaphyrin have not been determined yet, mainly due to the their instability under ambient conditions. On the other hand, perfluorinated [36]octaphyrin (**9**) was obtained in 4–7% yield from the reaction of 3,4-difluoropyrrole and pentafluorobenzaldehyde.[23] Interestingly, **9** takes a different conformation: it is not twisted figure-eight but has a round ellipsoidal structure (Figure 18, b). Mainly due to their nonplanar structures, these octaphyrins do not exhibit any aromatic or antiaromatic character.

Copper Metalation of [36]Octaphyrin and Perfluorinated [36]Octaphyrin

A solution of **5a** in toluene was stirred at 50 °C in the presence of ten equivalents of $Cu(OAc)_2$ and five equivalents of NaOAc and the metalation process was monitored by UV/Vis absorption spectroscopy. Compound **5a** exhibits absorption bands at 410 and 643 nm, which change to absorption bands at 412 and 668 nm after 2 h and then to absorption bands at 351 and 522 nm after 4 h (Figure 19). These spectral changes were ascribed to sequential formation of mono-Cu^{II} (**33**) and bis-Cu^{II} (**34**) complexes by comparison with the absorption spectra of authentic samples (Figure 20).[42] On further heating the small, shoulder-like absorption at 408 nm in the spectrum increased and finally

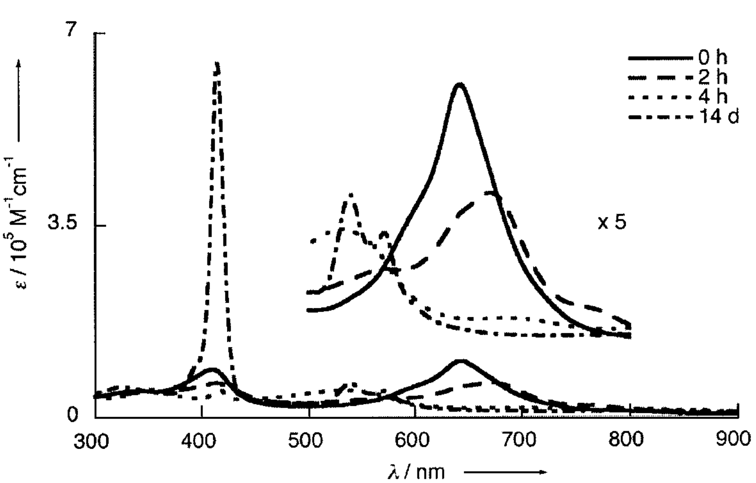


Figure 19. UV/Vis spectral changes recorded during metalation of **5a** with $Cu(OAc)_2$ at 50 °C in toluene.

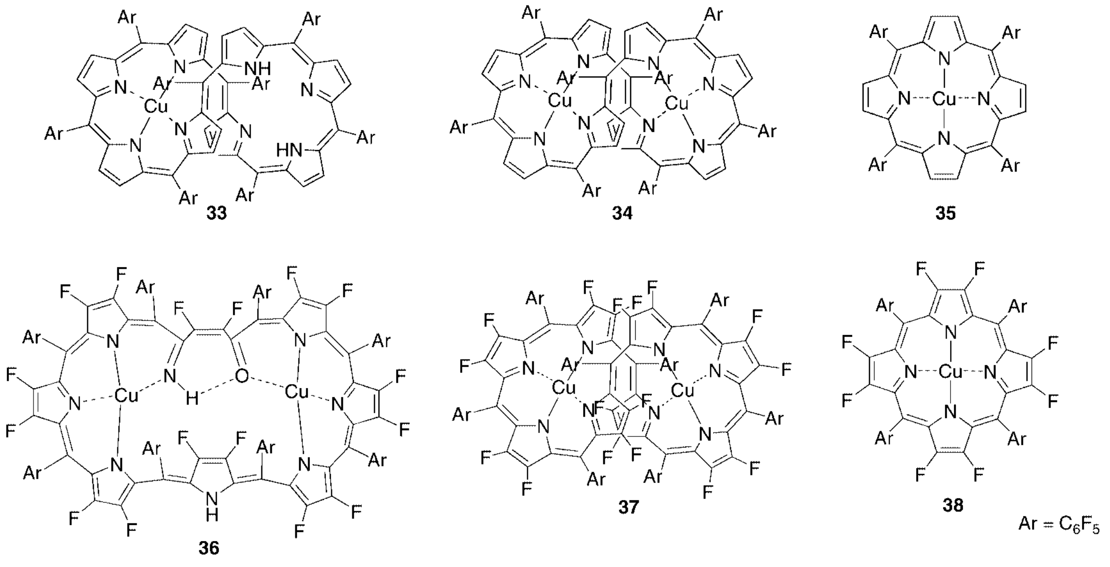


Figure 20. Copper complexes of octaphyrins and porphyrins.

the spectrum showed only the absorption at 408 nm with small bands at 535 and 570 nm after heating for two weeks (Figure 19). This final spectrum indicates the formation of the Cu^{II} porphyrin **35** (Figure 20). The mono-Cu^{II} complex **33** and the bis-Cu^{II} complex **34** were prepared in 77 and 81% yields, respectively, under temperature-controlled conditions in a CH_2Cl_2 solution with a small amount of MeOH. In the solid state, **34** takes a similar twisted figure-eight conformation with two copper ions bound inside the porphyrin-like tetrapyrrolic cores. The coordination of the Cu^{II} ions is severely distorted from square-planar coordination (Figure 21). Considering that neither free base **5a** nor **33** show splitting behavior, this structural feature suggests that the relief of strain in **34** may be the main driving force for this thermal splitting reaction.[42,43] We thus estimated the activation parameters of the splitting reaction by absorption spectroscopic analysis. The splitting reaction of **34** was found to be a unimolecular process with $\Delta H^{\ddagger}$ = 101 kJ mol^{-1} and $\Delta S^{\ddagger}$ = –23.5 J K^{-1} mol^{-1}. A possible mechanism of the splitting reaction may be a 2π + 2π cycloaddition process to give a spirocyclobutane intermediate, as shown in Scheme 5.

This thermal splitting reaction was also seen in the solid state. In the DSC experiment of **34**, a sharp exothermic re-

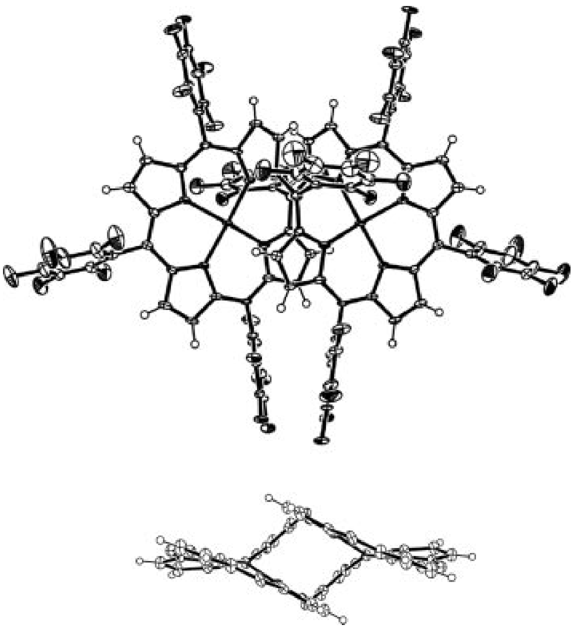
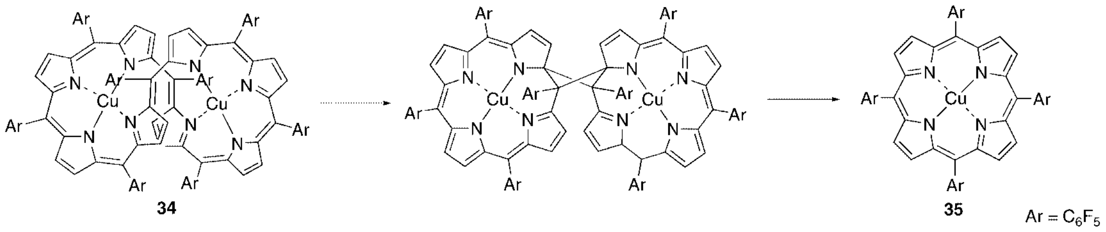


Figure 21. X-ray crystal structure of **34**; top view (top) and side-view (bottom). *meso*-Aryl substituents have been omitted for clarity in the side view.



Scheme 5. A possible mechanism of the splitting reaction of **34**.

sponse was observed between 240 and 280 °C, and **35** was obtained in high yield from this thermolysis experiment. The present thermal splitting reaction may be attractive for application as a recording device in light of the dramatic spectral changes and the perfect material balance. Fortunately, **34** was found to form a good transparent film when spin-coated onto quartz. A preliminary thermolysis experiment with this film indicated the more robust nature of **34** in the film up to 140 °C, but clean splitting into **35** at 200 °C.

A similar copper metalation reaction of perfluorinated [36]octaphyrin **9** revealed the formation of two bis-Cu^{II} metal complexes **36** and **37** in 58 and 14% yields, respectively, when treated with Cu(OAc)$_2$ and NaOAc in CH$_2$Cl$_2$ solution (Figure 20).[44] The crystal structure of **36** was determined by single-crystal X-ray analysis (Figure 22). It takes a bent, U-shaped, ellipsoidal conformation in which one pyrrole ring is hydrolytically cleaved to give a keto-imine moiety. One of the two copper ions is bound to the keto-carbonyl oxygen atom and the nitrogen atoms of the nearby tripyrrolic subunit, while the other copper ion is bound to the imine nitrogen atom and the nearby second tripyrrolic subunit. The minor product **37** exhibits an absorption spectrum that is quite similar to that of **34**, and the high-resolution ESI-TOF mass spectrum indicated the formation of the bis-Cu^{II} complex of perfluorinated [36]octaphyrin (**37**; Figure 20). Although efforts to obtain suitable crystals of **37** have been unsuccessful, these data suggest that **37** is a bis-Cu^{II} complex with a figure-eight structure similar to that of **34**. Thus, we tested the thermolysis reaction of **37** both in CH$_2$Cl$_2$ solution and in the solid state. Upon heating in solution it goes hydrolysis to give **36** with concomitant decomposition, whereas, interestingly, thermolysis in the solid state led to splitting into **38**. During the copper metalation of **9**, one possible route to **36** may be initial formation of **37** followed by subsequent hydrolytic ring opening of one pyrrole ring facilitated by the strongly electron-deficient nature of the perfluorinated macrocycle.

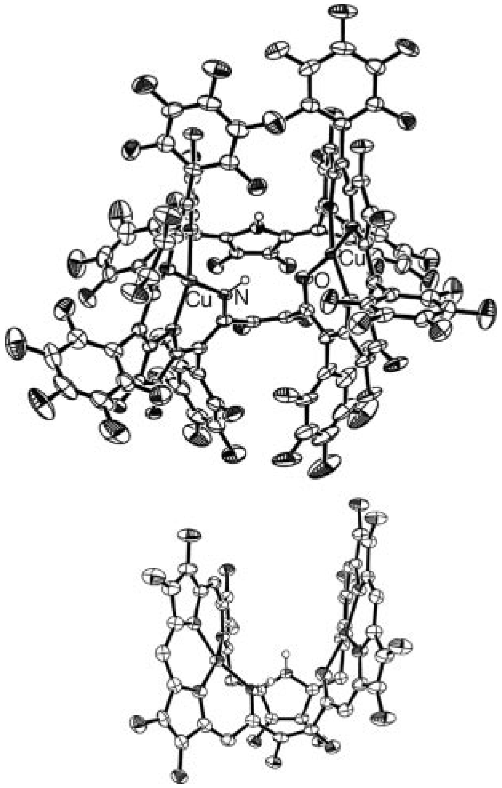


Figure 22. X-ray crystal structure of **36**; top view (top) and side view (bottom). *meso*-Aryl substituents have been omitted for clarity in the side view.

Silver Metalation of [36]Octaphyrin and Perfluorinated [36]Octaphyrin

Among the transition metal ions tested, we found the complexation of **5a** and **9** with a salt of silver, a heavier congener of copper, proceeded smoothly without any skeletal rearrangement of the macrocyclic ring, in sharp contrast to the metalations with copper, to provide similar bis-silver complexes **39** and **40** almost quantitatively despite the different structures of the free base (Figure 23).[44] The bound silver ions are in the Ag^{I} oxidation state judging from the coordination bond lengths and the diamagnetic nature of the complex observed in the ^{1}H NMR spectra, which indicates that [36]octaphyrin is oxidized to [34]octaphyrin by an excess amount of silver salt. The oxidized form acts as a divalent ligand to coordinate two Ag^{I} ions. Both structures exhibit almost C_2-symmetric figure-eight conformations with two silver ions bound within porphyrin-like tetrapyrrolic cavities with Ag–N bond lengths in the range of 2.27–2.40 Å (Figure 24). Interestingly, pentafluorophenyl substituents at the crossing *meso* position lie just above the silver atoms in parallel with the tripyrrolic units, with interplanar distances of approximately 3.2 Å, while the β-substituents (hydrogen and fluorine atoms) of pyrroles D and H are placed below the silver ions with Ag–β-carbon distances of 2.89 and 2.87 Å for **39** and 3.14 and 3.16 Å for **40**. This proximity between the Ag ions and the substituents was supported by the additional through-space coupling with Ag^{I} (I = 1/2) observed in the ^{1}H and ^{19}F NMR spectra. Despite the figure-eight structures, which are similar to that of **34**, both **39** and **40** are thermally stable and do not exhibit the splitting reactivity observed for **34**. A major reason for this may be the 34π-electron system of **39** and **40**. Considering the instability of free base [34]octaphyrin

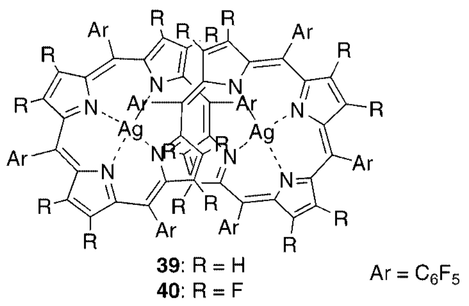


Figure 23. Bis-Ag^{I} complexes of octaphyrins.

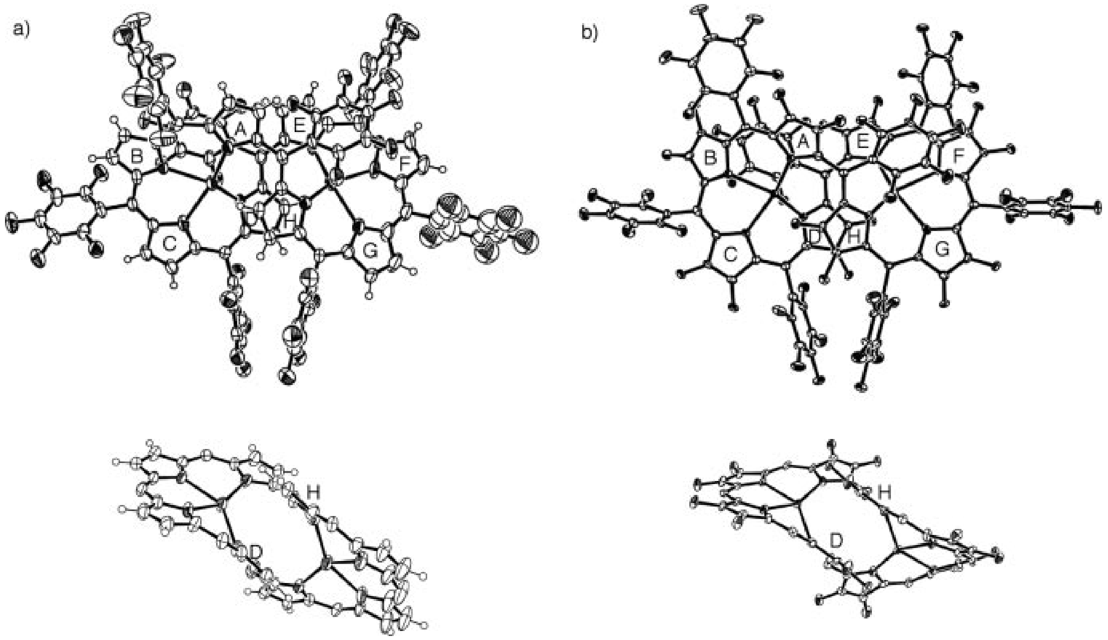


Figure 24. X-ray crystal structures of a) **39** and b) **40**; top views (top) and side views (bottom). *meso*-Aryl substituents have been omitted for clarity in the side views.

under ambient conditions, the oxidized octaphyrin ligands are stabilized by silver metalation. Despite the inertness of **39** and **40** upon heating, the Ag ions are easily removed upon reduction with $NaBH_4$ to provide the respective free base [38]octaphyrins.

Summary and Outlook

The novel properties of the free bases and their metal complexes of expanded porphyrins have been revealed to be highly promising for various applications, including multimetal chelation, catalysis, receptors of anions and neutral molecules, PDT sensitizers, MRI contrast agents, and nonlinear optical materials. The serendipitous discovery of the facile, one-pot synthesis of *meso*-aryl-substituted expanded porphyrins has allowed the investigation of their fruitful coordination chemistry, which, however, still remains in its early stages. Investigation of their metal-complexation reactions and their fascinating properties for further applications is still in progress in our laboratory.

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