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Synthesis of Antiaromatic Isophlorins and Studies of the Design Guidelines

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2026

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Preface: Overview of This Thesis

The studies on this thesis have been carried out under the direction of Prof. Dr. Takuji Ogawa, Prof. Dr. Takashi Kubo, and Prof. Dr. Shohei Saito since 2020 at Department of Chemistry, Graduate School of Science, The University of Osaka. Herein, the author systematically examined the structure-property relationship of isophlorin, an antiaromatic compound, to elucidate the fundamental concepts of “aromaticity” and “antiaromaticity” in organic chemistry through synthetic experiments and quantum chemical calculations.

Chapter 1 provides the historical context and theoretical concepts of aromaticity and antiaromaticity, emphasizing their synthesis and applications, especially in porphyrinoids. Understanding the concept of aromaticity and antiaromaticity is crucial in organic chemistry as it describes the properties of cyclic conjugated compounds. Aromatic compounds, such as porphyrinoids—which serve as the backbone of chlorophyll and heme—are stable. Antiaromatic compounds, in contrast, are unstable and rarely exist in nature; research on them has historically lagged that on aromatic compounds. However, in recent years, antiaromatic compounds have garnered interest due to their unique electronic structures, which differ from those of aromatic compounds, particularly characterized by a narrow HOMO–LUMO gap. Isophlorin, which has a similar structure to porphyrin, has not been synthesized or isolated due to its antiaromatic nature, which makes it prone to be oxidized, along with the significant steric hindrance caused by the NHs within the macrocycle. Recent research has led to the synthesis of antiaromatic isophlorin analogs through metal incorporation and the modification of the nitrogen atom with other heteroatoms. In this study, the author’s goal is to achieve the synthesis of stable antiaromatic isophlorin without metalation or core-modification. The author also aims to explore the structure-property correlation of antiaromatic compounds by synthesizing and analyzing various metal complexes and analogs of this antiaromatic isophlorin, ultimately establishing design guidelines for these compounds.

In Chapter 2, the antiaromatic isophlorins are synthesized without metalation or core-modification by introducing electron-withdrawing CN groups. Two-electron reduction of β -tetracyanoporphyrin with the mild reducing agent hydrazine monohydrate affords the corresponding isophlorin, indicating that antiaromatic compounds can be handled stably through precise molecular design.

In Chapter 3, metal complexes of the antiaromatic isophlorin, synthesized in Chapter 2, are explored. Two-electron reduction of the Zn(II), Pd(II), and Sn(IV) complexes is conducted to synthesize the isophlorin metal complexes, and the Sn(IV) complex is successfully obtained. The resulting isophlorin Sn(IV) complex exhibits a higher planar structure due to the introduction of the metal ion and stronger antiaromaticity compared to the metal-free isophlorin in Chapter 2.

Furthermore, in Chapter 4, lanthanide complexes of the antiaromatic isophlorin are

examined. The lanthanide ion is too large to fit inside the porphyrin macrocycle, resulting in a sandwich structure where two porphyrin ligands coordinate with one lanthanide ion. To synthesize an isophlorin sandwich complex, the reduction behavior of the β -tetracyanoporphyrin lanthanide complex is explored. Electrochemical measurements reveal that the β -tetracyanoporphyrin lanthanide complex can be reduced by four electrons. Further investigation of reducing agents may enable the synthesis of isophlorin sandwich complex.

The antiaromatic isophlorins synthesized in Chapters 2 and 3 require the introduction of numerous electron-withdrawing substituents for stabilization. Interested in the effect of substituents on antiaromaticity, in Chapter 5, the substituent effects on heteroatom-substituted antiaromatic isophlorin analogs are investigated using quantum chemical calculations. It is found that by changing the substituents, the frontier orbitals on isophlorin analogues change significantly, and the strength of antiaromaticity can be adjusted accordingly.

Chapter 6 summarizes this thesis. In this thesis, the author presents design guidelines for antiaromatic compounds through the synthesis and analysis of antiaromatic isophlorins, their metal complexes, and heteroatom-substituted analogues. A deeper understanding of antiaromaticity is achieved by systematically exploring the relationship between structure and properties from both experimental and computational perspectives. The insights gained from this thesis are expected to promote the synthesis of further antiaromatic compounds and contribute to applied research utilizing their characteristic electronic structures. Ultimately, this could lead to the development of novel functional molecules and materials.

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Chapter 1.

General Introduction: From Benzene to Isophlorin—An Overview of Aromaticity and Antiaromaticity

Abstract: This chapter presents an overview of the historical background and theoretical aspects of aromaticity and antiaromaticity. It also highlights recent research on notable antiaromatic compounds, with a particular focus on porphyrinoids. First, the electron counting rules for determining whether a compound is aromatic or antiaromatic are introduced, followed by various descriptors used to characterize the degree of aromaticity and antiaromaticity. After a brief summary of experimental advances in representative antiaromatic compounds, this chapter introduces porphyrinoids, which are aromatic compounds abundant in nature. This chapter also discusses the structural specificity of porphyrinoids and experimental studies on isophlorin, an antiaromatic porphyrinoid.

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1.1 Aromaticity and Antiaromaticity: Historical Overview

The concept of “aromaticity” and “antiaromaticity” play crucial roles in organic chemistry.^[1,2] It is well known that aromatic compounds are particularly stable and relatively unreactive, whereas antiaromatic compounds are unstable and highly reactive. This concept is indispensable because it provides a simple way to understand the stability of organic compounds and the mechanisms of their chemical reactions.^[3,4]

The history of “aromaticity” dates back nearly 200 years to the research of Michael Faraday.^[5,6] In 1825, Faraday isolated “bi-carburet of hydrogen,” or C_2H_4 , by distilling whale oil.^[7] This compound is believed to be benzene, the first “aromatic” molecule to be isolated. Eight years later, Mitscherlich synthesized Faraday’s “bi-carburet of hydrogen” by treating benzoic acid with calcium hydroxide. The authors claimed that Faraday’s carbon-to-hydrogen ratio was incorrect and suggested that the correct ratio was 1:1. He then named this compound “benzin.”^[8] Over time, compounds related to benzene and benzoic acid became recognized chemical terms. In 1855, August Wilhelm Hofmann first used the term “aromatic” to describe a group of acids related to benzene.^[9] Various debates persisted regarding the structure of benzene. In 1865, Kekulé proposed a cyclic structure consisting of alternating single and double bonds that is nearly identical to the structure accepted today.^[10]

Discussions regarding the stability of aromatic compounds advanced with developments in physical chemistry. In the early 1930s, John C. Slater^[11] and Linus Pauling^[12,13] explained the unique stability of benzene by proposing that the resonance between two Kekulé structures provides energetic stabilization. Around the same time, Erich Hückel used molecular orbital theory to explain exceptional stability of benzene, laying the foundation for the famous $4n+2$ rule of aromaticity.^[14–17] Doering and Detert refined this theory, establishing the $4n+2$ rule.^[18] Thus began the story of aromaticity. Since then, various rules have been proposed for determining whether a molecule is aromatic or not.^[19,20]

Planar cyclic π -conjugated compounds with $4n\pi$ electrons exhibit antiaromaticity.^[21] This concept of “Hückel’s antiaromaticity” was introduced by Chung and Dewar, and further advanced by Breslow.^[22,23] In 1961, Breslow introduced the term “antiaromatic” while proposing a 4π electron ring for the cyclopropenyl anions in the thiamine-catalyzed benzoin condensation reaction.

Chapter 1 describes the concepts of aromaticity and antiaromaticity, focusing particularly on antiaromatic compounds. Chapter 1.2 will discuss the electron-counting rules for aromaticity and indicators for estimating aromaticity and antiaromaticity. Chapter 1.3 covers antiaromatic compounds and their applications, which have attracted considerable interest in recent years. Chapter 1.4 discusses porphyrins, a type of aromatic compounds, and isophlorin, a type of antiaromatic compounds. Examples of porphyrinoid synthesis with antiaromatic properties are presented, and isophlorin, a representative antiaromatic porphyrinoid, is introduced.

1.2 Concepts of Aromatic and Antiaromatic Compounds

The term “aromaticity” was originally used to describe the properties of planar π -conjugated compounds such as benzene. Today, however, the term applies to any molecule with a two- or three-dimensional ring structure and highly delocalized π electrons. Because aromaticity is not a property that can be directly observed experimentally, it is difficult to define and quantify. Although the electron-counting rule is useful for distinguishing aromatic or antiaromatic compounds, it cannot provide a quantitative measure of aromaticity. Consequently, numerous descriptors of aromaticity based on energetic,^[24] structural,^[25] magnetic,^[26] electronic,^[27] and reactive^[28] properties have been proposed. However, none of these are universal, and each has its own ambiguities. Each descriptor indirectly measures a specific aspect of aromaticity. From this perspective, aromaticity is now considered a multidimensional phenomenon^[29,30] and should be quantified using a set of descriptors based on different aromaticity criteria rather than using a single descriptor.^[31] When multiple aromaticity indicators are used, especially when all criteria show the same trend, conclusions regarding aromaticity generally become far more reliable. “Aromaticity” is a superposition of multiple physical phenomena that must be discussed experimentally and theoretically from various perspectives.

This chapter begins with an introduction to the primary counting rules for aromaticity, continues with indicators for quantifying aromaticity, and concludes with a discussion of the antiaromatic compounds, that have received significant attention in recent years.

1.2.1 Electron Counting Rules of Aromaticity

The electron counting rule is useful in organic chemistry because it allows chemists to determine the number of π electrons in a compound, predict its aromaticity, and consequently, its physical properties. The counting rule for simple monocyclic π -conjugated compounds, represented by benzene, is expressed by the Hückel rule, as shown in Chapter 1.2.1.1. In Hückel aromatic compounds, the molecular orbitals are perfectly in the same phase. Chapter 1.2.1.2 addresses molecules in which phase inversion occurs within the molecular orbitals. In such cases, as exemplified by molecules with Möbius structures, aromaticity follows the Möbius rule rather than the Hückel rule. Chapters 1.2.1.1 and 1.2.1.2 focus on the aromaticity of molecules in their ground state. Chapter 1.2.1.3 explores the aromaticity of molecules in excited states. Chapter 1.2.1.4 states that for polycyclic aromatic hydrocarbons (PAHs), where multiple benzene rings are fused, it is essential to consider resonance structures based on the Clar rule. Chapters 1.2.1.5 and 1.2.1.6 discuss three-dimensional aromaticity and stacked-ring aromaticity, respectively. These theories were developed through the interplay between theoretical and experimental studies. There are many instances in which the theoretically proposed aromaticity has been confirmed experimentally, and vice versa. In addition to these examples, the concept of aromaticity continues to expand, as in the case of large cylindrical molecules.^[32] Recent research has aimed to integrate these concepts and create simpler

frameworks.^[33,34] Although the concept of aromaticity is useful for describing the stability and physical properties of compounds, some caution against attributing the stability of all π -conjugated compounds solely to “aromaticity.”^[4,20]

1.2.1.1 Hückel’s $(4n+2)\pi$ Rule

The Hückel rule is a classic electron counting rule for aromaticity and antiaromaticity. According to this rule, planar cyclic π -conjugated compounds are classified as aromatic if they possess $(4n+2)\pi$ electrons, and as antiaromatic if they possess $4n\pi$ electrons. Cyclic π -conjugated compounds with non-planar structures are classified as nonaromatic. For monocyclic molecules with the maximum number of conjugated bonds (annulenes, C_nH_n) with D_{Nh} symmetry, the most stable molecular orbital (MO) involves the superposition of both p_z atomic orbitals in the same phase (Figure 1.1a, which shows the p_z atomic orbitals of benzene^[19]).

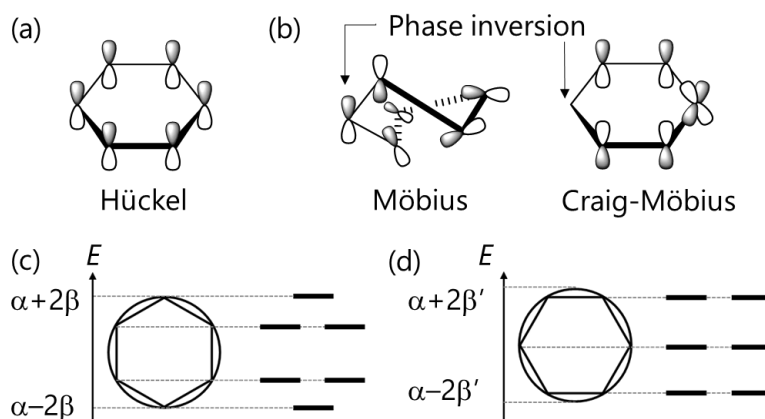


Figure 1.1 Orbital distribution in Hückel and Möbius topologies. (a) $2p_z$ atomic orbitals of benzene with in-phase overlap. (b) $2p_z$ atomic orbitals in Möbius aromatic compounds, either an organic system with a twisted structure or a metalla-aromatic annulene containing a metal ion acting as a phase inversion. (c) MO diagram of a Hückel and (d) Möbius aromatic compound.

The remaining MOs are doubly degenerate, except for the highest-energy orbital in the cyclic π -conjugated compounds. Solving the time-dependent equation allows us to determine the energy of each molecular orbital, E_k (Figure 1.1c and Equation (1)), where N is the number of p orbitals, α is the energy of p orbitals, and β represents the interaction between neighboring p orbitals. As the phase inversion occurs an even number of times in Hückel aromatic conjugated molecules, the $2k$ value is introduced using the following equation:

$$E_k = \alpha - 2\beta \cos \frac{(2k)\pi}{N} \quad (1)$$

Representing these E_k values using Frost circles enables visual understanding of the molecular

orbitals.^[35] Using this MO distribution, the closed-shell electronic structure is obtained with 2, 6, 10, 14... π electrons, i.e., $4n+2\pi$ electrons according to Hückel's rule ($n = 1, 2, 3...$). In 1954, Doering and Knox synthesized the cycloheptatrienyl cation ($C_7H_7^+$), which indeed exhibited a large “resonance stabilization quantity,” providing one of the first experimental confirmations of this rule.^[36]

Planar cyclic π -conjugated compounds with $4n\pi$ electrons are antiaromatic.^[21] This concept of “Hückel's antiaromaticity” was introduced by Chung and Dewar, and advanced by Breslow.^[22,23] Aromatic compounds have a closed-shell structure with four electrons in the highest occupied molecular orbital (HOMO), resulting in a stable structure (Figure 1.2a). In contrast, ideal antiaromatic compounds have two electrons in their HOMO, forming an open-shell structure that is inherently unstable (Figure 1.2b). To resolve this instability, many antiaromatic compounds undergo bond rearrangement and structural distortions in their actual states to resolve their degeneracy and, transform into more stable closed-shell states (Figure 1.2c). At this point, the HOMO and lowest unoccupied molecular orbital (LUMO) are formed from the two originally degenerate orbitals, and the antiaromatic compounds are characterized by inherently narrow HOMO–LUMO gaps.^[37]

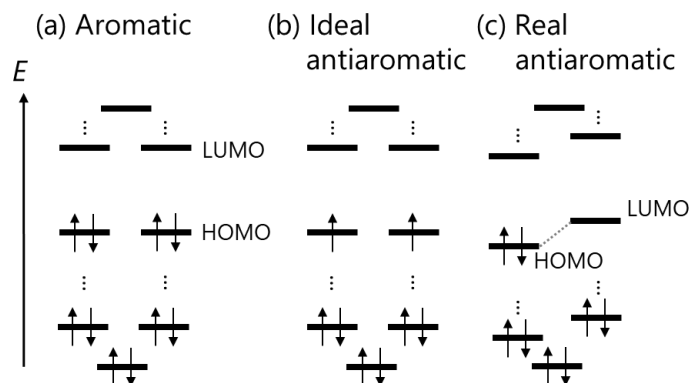


Figure 1.2 Energy diagram for (a) aromatic, (b) ideal and (c) real antiaromatic compounds.

1.2.1.2 Möbius' $4n\pi$ Rule

The Möbius rule explains the aromaticity of π -conjugated molecules with a twisted structure (Figure 1.1b left) or containing a metal ion as a phase inversion (Figure 1.1b right). According to Möbius rule, a π -conjugated molecule with one phase inversion in the most stable molecular orbital (MO) can be classified as aromatic if they possess $4n\pi$ electrons, and as antiaromatic if they possess $(4n+2)\pi$ electrons. This is because the MO phase in the Möbius molecule undergoes one inversion in its most stable state. This necessitated an odd number of inversions ($2k+1$) for other MOs (Figure 1.1d).

$$E_k = \alpha - 2\beta' \cos \frac{(2k+1)\pi}{N} \quad (2)$$

Möbius aromaticity was first described theoretically in organometallic systems by Craig and Paddock,^[38] and six years later, further elaborated by Heilbronner for annulene.^[39] Experimentally,

Möbius aromatic compound was first reported in 2003 (Figure 1.3a),^[40] but detailed quantum chemical calculations revealed that this compound is nonaromatic.^[41] Stępień et al. synthesized the first dynamic Hückel–Möbius system (Figure 1.3b).^[42] Metalla-aromatic compounds, also known as Craig–Möbius aromatic compounds, can be obtained without introducing a twist into the molecular structure.^[43]

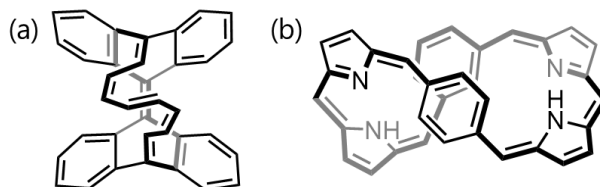


Figure 1.3 Molecular structure of synthesized Möbius aromatic compounds (a) reported by Herges et al.,^[40] and (b) by Stępień et al.^[42]

1.2.1.3 Baird's $4n\pi$ Rule

The Baird's rule describes the aromaticity and antiaromaticity in the lowest triplet excited state (T_1) of annulenes. When a cyclic annulene is in its T_1 state, those with $4n\pi$ electrons exhibit aromatic properties, while those with $(4n+2)\pi$ electrons exhibit antiaromatic properties.^[33,44,45]

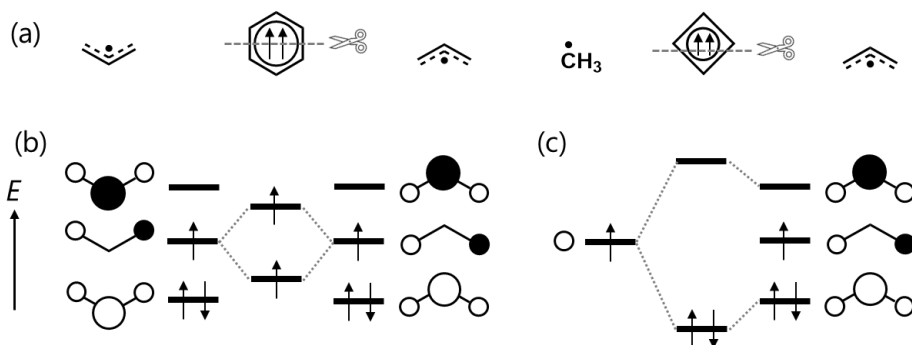


Figure 1.4 (a) Decomposition of benzene and cyclobutadiene into two polyenyl monoradical fragments with odd numbers of carbon atoms. (b) Energy diagram of π -orbital interactions between the fragments. Benzene is destabilized by type I SOMO–SOMO interactions, while cyclobutadiene is stabilized by type II SOMO–MO interactions.

According to his theory, annulene was decomposed into two polyenyl monoradical fragments with odd numbers of carbon atoms, and the π -orbital interactions of these fragments were examined. One is a type I interaction between two singly occupied molecular orbitals (SOMOs), and the other is a type II interaction between the SOMO of one fragment and the occupied or unoccupied MOs of the other fragment. Taking benzene and cyclobutadiene as examples, benzene can be split into two propenyl radicals and is destabilized by type I SOMO–SOMO interactions (Figures 1.4a, c). In contrast, cyclobutadiene is stabilized by type II SOMO–MO interactions (Figures 1.4b, d). Generalizing this

theory, compounds with $(4n+2)\pi$ electrons are destabilized, i.e., antiaromatic, while compounds with $4n\pi$ electrons are stabilized, i.e., aromatic, in the lowest excited triplet state. Although Baird's rule was derived only for the T_1 state, several computational and experimental studies have shown that Baird's rule can also be applied to the S_1 state.^[46–48] However, these are less rigorous than Baird's rule, so caution is required when discussing aromaticity and antiaromaticity in singlet states.

Experimental evidence for aromaticity in the excited state was obtained from the spectroscopic measurements of the photochemical solvolysis of fluoren-9-ol (Figure 1.5).^[46,49] The authors noted that the solvolysis was “believed to be the formation of an aromatic 4π cationic system in the excited state.” The Baird's rule is widely applicable for explaining photochemical reactivity and photophysical as well as photochemical properties.^[33]

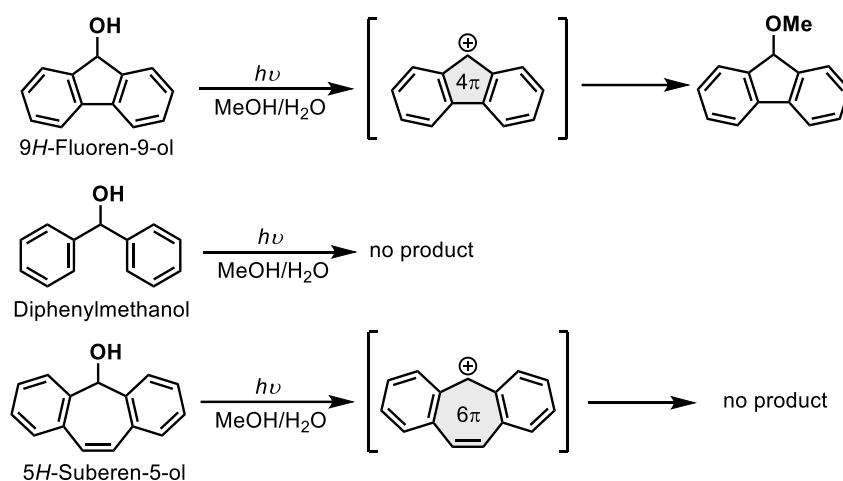


Figure 1.5 Photosolvolysis of 9H-fluoren-9-ol, diphenylmethanol, and 5H-suberen-5-ol.^[46] 9H-Fluoren-9-ol undergoes photosolvolysis while diphenylmethanol and 5H-suberen-5-ol do not. 9H-Fluoren-9-ol possesses a 4π cyclic structure via a dehydroxylation and, in the excited state, undergoes aromatic stabilization according to the Baird's rule. In contrast, diphenylmethanol does not have a cyclic conjugated system resulting from a dehydroxylation, and 5H-suberen-5-ol has a 6π electron system that is destabilized in the excited state.

1.2.1.4 Clar's Sextet Rule

Strictly speaking, the aromaticity rules mentioned above—the Hückel rule, Möbius rule, and Baird's rule—all apply only to monocyclic π -conjugated systems. When a major $[N]$ annulene-type resonance structure exists within a molecule, these rules can be extended to polycyclic π -conjugated systems. On the other hand, fully benzene-type PAHs typically exhibit localized aromaticity, where π electrons are primarily localized on the benzene ring, because the benzene possess significantly large stabilization energies. This is well described as the Clar's sextet rule, where among polycyclic aromatic hydrocarbons of identical composition, the isomer with the highest number of aromatic π -sextet rings exhibits the greatest stability. An aromatic π -sextet is defined as six π electrons localized

within a single benzene-like ring separated from adjacent rings by a formal C–C single bond. For example, in resonance structure **a** of phenanthrene in Figure 1.6, only the central ring possesses a π -sextet. Therefore, applying this rule to phenanthrene indicates that resonance structure **a** is less important than resonance structure **b**, which possesses two π -sextets, for explaining the properties and aromaticity of phenanthrene. Thus, the outer rings of phenanthrene are expected to exhibit a greater proportion of local aromaticity than the central ring. The central benzene ring exhibits a more double-bond-like character than that of surrounding benzene rings and is highly reactive.^[50]

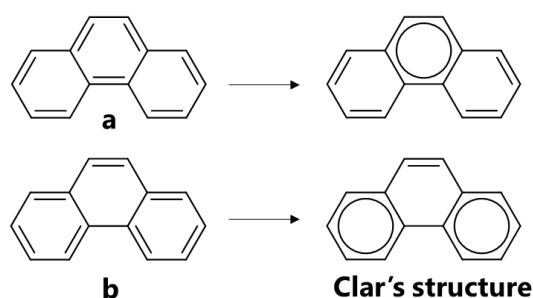


Figure 1.6 From the Kekulé resonance structures of phenanthrene, the corresponding Clar aromatic π -sextet rings are extracted and indicated by a circle. The structure with the highest number of aromatic π -sextets is the so-called Clar's structure.

1.2.1.5 Three-Dimensional Aromaticity

The concept of aromaticity can be extended to three-dimensional π -conjugated systems. An example is the spherical aromaticity in fullerenes proposed by Hirsch in 2000, whose resulting $2(n+1)^2$ rule is the spherical counterpart to the $(4n+2)\pi$ rule in cyclic annulene systems.^[51,52] It should be noted that Hirsch's rule applies to highly symmetric three-dimensional π -conjugated systems such as fullerene (C_{60}). Furthermore, applying Baird's rule to Hirsch's conceptual framework led to the recognition of open-shell spherical aromaticity. This predicts that spherical species possessing $(2n^2+2n+1)\pi$ electrons and a spin state $S = n + 1/2$ exhibit aromaticity.^[53] This spherical aromaticity is applicable to certain metal or boron clusters, as well as highly symmetric PAHs.^[54,55]

1.2.1.6 Stacked-Ring Aromaticity

When $(4n+2)\pi$ aromatic compounds are stacked, they twist or shift relative to one another due to dispersion forces from the abundance of delocalized π electrons.^[56] In this type of aromatic compound stacking, face-to-face arrangements are avoided because the dominant force is repulsive interaction caused by electronic repulsion. The interplanar distance in these stackings measures approximately 3.4 to 3.5 Å, which corresponds to the sum of the van der Waals radii of sp^2 -carbon atoms. Cyclophanes, in which two $(4n+2)\pi$ aromatic rings are positioned opposite each other at a distance of less than 3.4 Å, have been shown to be unstable.^[57,58] In 2007, Schleyer et al. proposed that face-to-face dimers of $4n\pi$ antiaromatic rings can exhibit aromaticity.^[59] This aromaticity arises

from the interaction of the HOMOs of two $4n\pi$ antiaromatic compounds to create a new, doubly degenerate, closed-shell HOMO like that of an aromatic molecule, which has a stabilizing effect on the original HOMO (Figure 1.7). Aihara expanded upon Schleyer's theory and introduced the concept of stacked-ring aromaticity (SRA), which refers to the aromaticity that arises from the π - π stacking of two or more cyclic π -conjugated systems.^[60] The theory of stacked-ring aromaticity was experimentally demonstrated using stacked antiaromatic porphyrin derivatives.^[61]

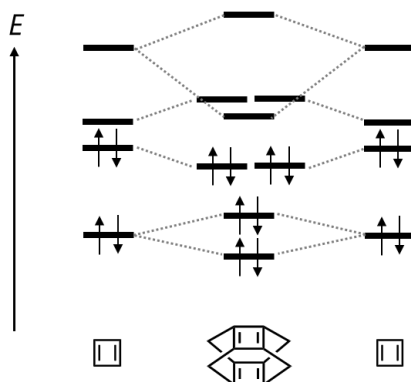


Figure 1.7 Energy diagram of antiaromatic cyclobutadiene and its face-to-face dimer. The stacking of cyclobutadienes provides a stabilizing effect, resulting in aromaticity.

1.2.2 Aromatic and Antiaromatic Descriptors

Aromatic compounds exhibit enhanced thermodynamic stabilities, uniform bond lengths, highly symmetric structures, distinctive reactivities, and unique magnetic and spectroscopic properties.^[62] The criteria for “aromaticity” are derived from these properties. However, because “aromaticity” is a multifaceted phenomenon, multiple factors must be considered to explain it comprehensively, both experimentally and theoretically.^[2,20,63,64]

To quantify the “aromaticity” of a molecule, evaluations should be considered from four perspectives: energetic, geometric, magnetic, and electronic. Energetic indicators assess the energy stabilization of the molecule. Geometric indicators are used to evaluate aromaticity based on bond length uniformity and molecular symmetry. Magnetic indicators assess the response of a molecule to an external magnetic field, whereas electronic indicators measure the degree of electron delocalization in the compound. This chapter provides a comprehensive explanation of the common indices, organized according to these four perspectives.

1.2.2.1 Energetic Indices

An important aspect of aromatic compounds is their enhanced energetic/thermodynamic and chemical/kinetic stability. Energetic indices are used to evaluate the stabilization energies of these

aromatic compounds; however, it is difficult to isolate the stabilization energy from other effects. The most commonly used method is to evaluate the aromatic stabilization energy (ASE) using homodesmotic or isodesmotic reactions.^[24,65] As an aromatic descriptor, the ASE is positive for aromatic compounds and negative for antiaromatic compounds. Calculating the ASE requires a reference reaction, and finding an appropriate reference can sometimes be difficult.

1.2.2.1 Geometric Indices

Geometric indices evaluate aromaticity based on bond length uniformity and molecular symmetry.^[25] Cyclic conjugated compounds with high aromaticity or antiaromaticity exhibit equalized bond lengths and high molecular symmetries. Experimentally, geometric indices are calculated using the crystal structure of the molecule. Theoretically, they are calculated using bond lengths obtained from the most stable structure determined by DFT calculations or something else. The harmonic oscillator model of aromaticity (HOMA),^[66] one of the geometric indices, evaluates aromaticity based on bond length data, using following equation:

$$HOMA(A) = 1 - \frac{1}{n} \sum_i^n \alpha_i (r_{opt} - r_{A_i, A_{i+1}})^2 \quad (3)$$

where α_i is an empirical constant that depends on the bond type in the molecule, and $r_{A,B}$ is the distance between atoms A and B. HOMA is calculated by comparing the bond lengths ($r_{A,B}$) to the “ideal bond lengths” of a reference molecule (r_{opt}), which introduces potential subjectivity in determining the reference value. The HOMA value is close to 1 for aromatic compounds and ideally antiaromatic compounds, and shows small or negative values for nonaromatic compounds. Bond length alternation (BLA)^[67] compares the average bond lengths within a single molecule and serves as an indicator of aromaticity.

$$BLA(A) = \frac{1}{2} \sum_{i=1}^n |r_{A_i, A_{i+1}} - r_{A_{i+1}, A_{i+2}}| \quad (4)$$

The BLA directly measures the bond length equalization expected in the aromatic pathway and does not require the reference data. The BLA values of the aromatic compounds are close to zero.

1.2.2.2 Magnetic Indices

Magnetic indicators measure the response of a molecule to an external magnetic field in order to evaluate its aromaticity.^[26] It is important to note that this indicator is not intrinsic, but a response-based indicator. Experimentally, it is investigated using chemical shifts in ^1H NMR via nuclear magnetic resonance spectroscopy (NMR). Theoretically, it is evaluated using nucleus-independent chemical shift (NICS), the anisotropy of the induced current density method (AICD), and the gauge-inclusive magnetic induction current method (GIMIC).

In ^1H NMR measurements of aromatic compounds, atoms inside the diatropic ring current

are shielded, causing the ^1H NMR peaks to shift upfield (Figure 1.8a). Atoms outside the diatropic ring current are de-shielded, causing the peaks to shift downfield. In the case of antiaromatic compounds, the direction of the ring current is reversed, resulting in the opposite behavior (Figure 1.8b). That is, atoms inside the paratropic ring current are de-shielded, causing peaks to shift downfield, whereas atoms outside are shielded, causing peaks to shift upfield. Therefore, the chemical shift of cyclic π -conjugated compounds serves as a criterion for determining the aromaticity or antiaromaticity.

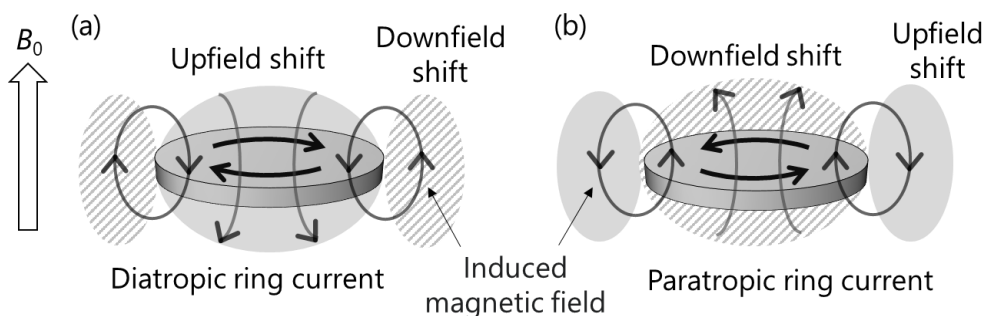


Figure 1.8 Differences in magnetic responsiveness between (a) aromatic and (b) antiaromatic compounds under an external magnetic field.

The NICS is widely used as a theoretical magnetic descriptor of aromaticity.^[68,69] NICS is defined as the negative value of the absolute magnetic shielding calculated at the center of a ring or at other relevant points in the system and is commonly, denoted as NICS(0). The “0” indicates that the NICS value is calculated within the molecular plane, whereas NICS(1) refers to the calculations performed 1 Å above the molecular plane. NICS values calculated inside the ring of an aromatic compound are negative, whereas those calculated inside an antiaromatic ring are positive. The NICS value calculated outside aromatic or antiaromatic rings generally have the opposite sign to those calculated inside, regardless of whether that “outside” is inside a nonaromatic ring. Care should be taken when calculating and interpreting NICS values, and in assessing whether they are meaningful.^[70]

The AICD^[71] and the GIMIC^[72] have become standard techniques for evaluating the overall aromaticity of cyclic π -conjugated compounds. These methods enable the direct classification of compounds as aromatic, indicated by diatropic ring currents, or antiaromatic, indicated by paratropic ring currents induced by an external magnetic field. A key advantage of the AICD is its independence from molecular orientation, whereas a key advantage of the GIMIC is its ability to calculate antiaromaticity in the presence of paratropic ring currents induced by an external magnetic field.^[2] This ability allows for a clear classification when paratropic ring currents are present.

1.2.2.3 Electronic Indices

Energetic, geometric, and magnetic indices have long been used as indicators of aromaticity. Electronic indices are a relatively new class of indicators for evaluating aromaticity based on

molecular electronic structures.^[27] Electronic indices cannot be calculated experimentally and require a theoretical discussion. Various electronic indices such as I_{ring} , MCI, FLU, BOA, AV1245, and AV_{min} have been proposed. Here, their derivations are omitted, leaving them to the respective literature, and only a brief overview is provided.

I_{ring} is a multicenter index that quantifies the electron delocalization along the ring.^[73] Antiaromatic and nonaromatic compounds have near-zero value in I_{ring} , while aromatic compounds have positive values. The aromatic fluctuation index (FLU) measures electron delocalization and evaluates aromaticity by comparison with a reference.^[74] FLU values are close to zero for aromatic compounds and large for antiaromatic compounds. The bond-order alternation (BOA) index evaluates aromaticity based on bond order.^[75] BOA is the electronic counterpart of BLA, just as FLU is the electron-structure equivalent descriptor of HOMA. It yields values close to zero for aromatic and nonaromatic compounds, and large positive values for antiaromatic compounds. The most rigorous electronic aromaticity index is the multicenter index (MCI).^[76] MCI sums all possible I_{ring} contributions obtained from atom permutations. The MCI yields large positive values for aromatic compounds and values close to zero for antiaromatic and nonaromatic compounds. Although the MCI can be applied to small molecules with up to 12 atoms incorporated into the conjugated system, AV1245 targets larger molecules.^[77] AV1245 represents the degree of π electron delocalization, related to energetic and magnetic properties. Similarly, the FLU, BOA, HOMA, and BLA aromaticity indices can also exhibit this limitation because they are based on average values. To evaluate aromaticity and antiaromaticity more quantitatively, the minimal absolute value AV_{min} of AV1245 was used. Some studies have stated that the electronic parameter AV_{min} best describes aromaticity.^[78]

1.3 Research on Antiaromatic Compounds

Aromatic compounds (especially Hückel aromatic compounds) form the foundation of a wide range of products, including plastics, pharmaceuticals, fragrances, dyes, functional polymers, and organic EL materials.^[1,2,79] However, research on antiaromatic compounds has not advanced as much as research on aromatic compounds, owing to the instability of antiaromatic compounds. Nevertheless, their unique electronic structures, such as narrow HOMO–LUMO gaps, have attracted significant attention in recent years.^[80,81]

Generally, antiaromatic compounds exhibit increasingly negative stabilization energies as the ring size decreases, indicating that they become increasingly unstable.^[82–85] This occurs because as ring size increases, the stabilizing effect from electron delocalization diminishes as ring size increases or because increased degrees of freedom cause a loss of planarity.

Cyclobutadiene (CBD) and cyclooctatetraene (COT) are the simplest molecules in the $4n\pi$ electron system but exhibit nonaromaticity rather than antiaromaticity (Figure 1.9). According to

Hückel rule, $4n\pi$ electron molecules possess open-shell triplet orbitals. However, the Jahn–Teller distortion in these molecules lifts their orbital degeneracy, transforming them into closed-shell orbitals with a narrow HOMO–LUMO gap. Thus, relatively small antiaromatic compounds such as CBD and COT, often become nonaromatic compounds because of the structural strain required to avoid antiaromaticity. Attempts to isolate CBD began with Kekulé’s efforts in 1872 and were pursued using various methods.^[86] One approach involves introducing bulky substituents around the CBDs to enhance thermodynamic stability. Kimling and Krebs synthesized bulky-substituted CBD in 1972, and Maier in 1978, each by protecting the periphery (Figure 1.9a).^[87,88] X-ray crystal structures showed that the isolated CBDs exhibited strong bond alternation, indicating that they were nonaromatic rather than antiaromatic. Another approach is wrapping in capsules. Cram et al. synthesized a non-substituted CBD by the CBD-forming reaction inside the cavity of a hemicarcerand (Figure 1.9b).^[89]

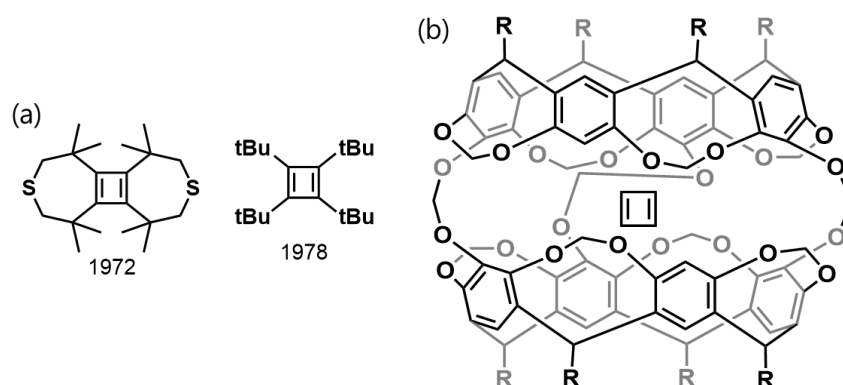


Figure 1.9 Synthetic efforts to prepare CBDs. (a) Introducing bulky substituents around the CBDs periphery, reported in 1972^[87] and 1978^[88], and (b) wrapping the non-substituted CBD in capsules to improve the kinetic stability.^[89]

COT is the first $4n\pi$ electron molecule synthesized.^[90] Unexpectedly it was found that this molecule behaved like an olefin. When planarized it was easily brominated at its double bonds instead of reacting by substitution. Anet conducted an NMR investigation using the isotopically labeled COT, revealing that the COT possesses two distinct nonaromatic D_{2d} structures as stable conformations and adopts the D_{8h} structure, an ideal Hückel antiaromatic structure, as its transition state (Figure 1.10).

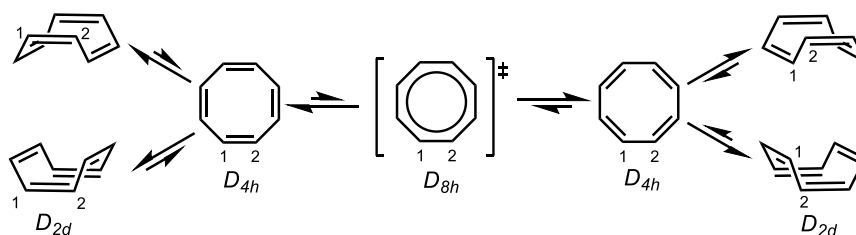


Figure 1.10 Schematic representation of the ring inversion process of D_{2d} -symmetrical COT via a D_{8h} -symmetrical transition state.

Subsequent studies revealed that stable, planar COT structures could be synthesized by cyclizing its periphery.^[91,92] In particular, fusing nonaromatic rings (Figure 1.11a),^[93–95] π -conjugated rings (Figure 1.11b),^[96] or porphyrin rings (Figure 1.11c)^[97,98] around the COT can induce strong paratoropicity in the COT rings.

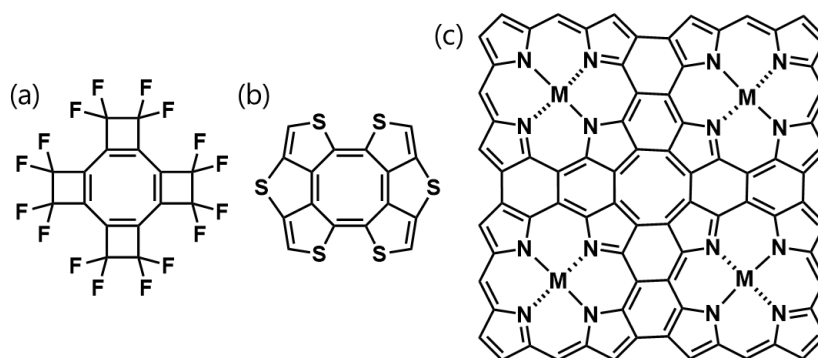


Figure 1.11 Planarized COT by fusing (a) nonaromatic rings, (b) thiophenes, or (c) porphyrin rings.

Pentalene is a bicyclic conjugated system possessing 8π electrons and can therefore be regarded as a short-circuited COT (Figure 1.12). Unsubstituted pentalene dimerizes at cryogenic temperatures, forms stable complexes with metals, and exhibits properties similar to those of $[4n]$ annulene.^[99] Relatively stable pentalene derivatives with antiaromaticity have been synthesized by introducing bulky substituents^[100,101] or by fusing aromatic rings, such as phenyl groups, to the periphery of the ring.^[102–104] Pentalene and its derivatives, especially dibenzo[*a,e*]pentalene, are relatively stable and can be easily synthesized. They can be applied in various ways, such as incorporating them into cyclized structures, MOFs or polymers.^[105–107] On the other hand, dibenzo[*a,f*]pentalene, a derivative of dibenzo[*a,e*]pentalene with a different benzene-fused position, is known to exhibit strong antiaromaticity and open-shell singlet biradical characteristics, making it unstable.^[104] *s*-Indacene is a 12π electron, tricyclic antiaromatic compound, which also employs benzene-fused systems and bulky substituents to enhance stability (Figure 1.12).^[108,109]

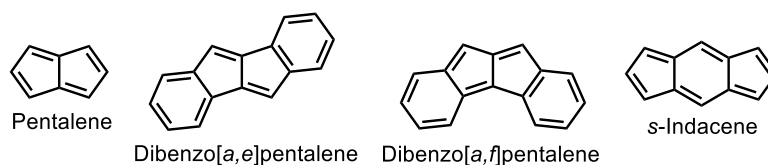


Figure 1.12 Chemical structures of pentalene, dibenzo[*b,f*]pentalene and *s*-indacene.

The synthesis of larger antiaromatic annulenes was achieved by Sondheimer et al.^[110] As the conjugated system expands, the molecular structure becomes more flexible and possesses multiple stable conformations. To experimentally investigate aromaticity and antiaromaticity, ^1H NMR

measurements were performed to discuss antiaromaticity from a magnetic perspective; however, observing the ring current effects was difficult except under low-temperature conditions. For example, an annulene with 16π electrons shows only a singlet peak at $35\text{ }^{\circ}\text{C}$. However, lowering the temperature to $-120\text{ }^{\circ}\text{C}$ reveals two singlet peaks. The effects of the paramagnetic ring current can be observed by lowering the temperature and suppressing ring motion. Thus, larger aromatic annulenes have more flexible structures, making it difficult to observe the ring currents at room temperature. Consequently, porphyrin analogs, which possess more π electrons and facilitate redox reactions more readily and exhibit greater structural rigidity than those of annulenes, have gained attention. Porphyrin derivatives are discussed in detail later in this chapter.

Antiaromatic compounds have useful applications in chemistry and show markedly different chemical properties and reactivity compared to aromatic compounds. Breslow hypothesized that increased antiaromaticity enhances the molecular conductivity,^[111] which is supported by some experiments.^[112–114] Applications utilizing the narrow HOMO–LUMO gap of antiaromatic compounds have been reported in organic field-effect transistors (OFETs)^[115–117] and organic solar cells.^[117,118] These redox-responsive $4n\pi$ electron cores facilitate reversible transitions among insulating, semiconducting, and metallic states, and are anticipated to have applications in molecular switches and data storage.^[81,119] Extended $4n\pi$ antiaromatic systems exhibiting diradical character possess potential applications as electronic and magnetic materials.^[120,121] A benzene-fused $4n\pi$ -conjugated ring, stabilized in the T_1 state relative to the S_1 state, is a candidate for a singlet-fission chromophore (Figure 1.13a).^[122,123]

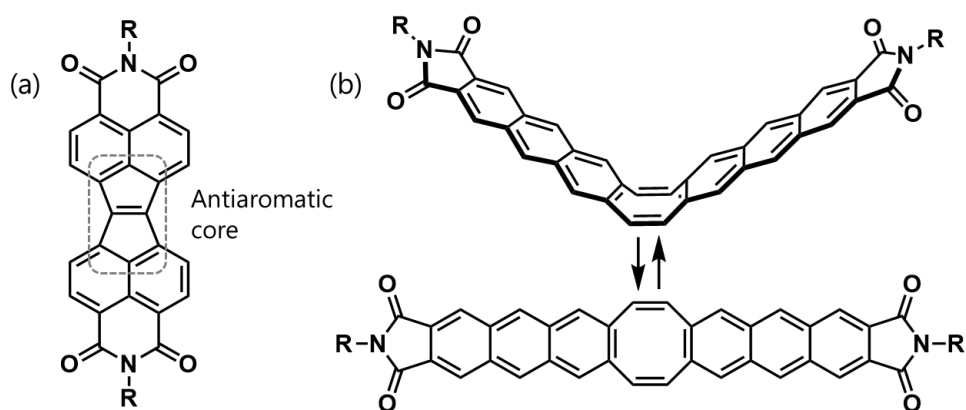


Figure 1.13 Structures of antiaromatic compounds with diverse functionalities. (a) Molecules with antiaromatic cores that exhibit singlet fission. (c) A luminescent molecule containing COT ring. Due to the tub and planar structure of COT ring, this molecule exhibits two different colors of emission.

The $4n\pi$ electron ring adopts a distorted structure in the S_0 state to avoid $4n\pi$ antiaromaticity but flattens in the S_1 state due to the emergence of excited-state aromaticity (Chapter 1.2.1.3, Figure

1.10). This property is utilized to design dual-emission molecules or small-molecule long-wavelength emitting dyes (Figure 1.13b).^[124–126] In this way, research on antiaromatic compounds not only presents challenges in synthesis, but also allows for the creation of functional materials by taking advantage of their distinct properties compared with those of aromatic compounds.

1.4 Porphyrinoids: From Aromatic to Antiaromatic with Focus on the Isophlorin

Many colored substances exist in nature, such as vegetables, fruits, and meat. These colors originate from natural pigments such as chlorophyll and heme.^[127,128] The backbone of chlorophyll and heme are collectively termed porphyrin compounds, which feature a structure in which four five-membered rings containing nitrogen atoms are connected cyclically. Porphyrin compounds have highly planar structure, and they are Hückel aromatic with 18π electron systems. They absorb visible light and exhibit vivid colors. Furthermore, the inward-facing nitrogen atoms can coordinate with nearly all metal ions, forming highly stable metal complexes. Various porphyrin analogs have been synthesized by varying the peripheral substituents and metal ions, and are widely used as pigments and catalysts.^[129–131] The cyclic tetrapyrrole structure of porphyrins was first proposed by William Küster in 1912,^[132] which paved the way for Hans Fischer, known as the “father” of porphyrin chemistry.^[133]

In this chapter, the research on porphyrins and their analogs is discussed, primarily focusing on their structural specificity. Subsequently, porphyrinoids that possess $4n\pi$ electrons and antiaromaticity are described, concluding with an introduction to isophlorin, a type of 20π antiaromatic porphyrinoid.

1.4.1 Aromatic Porphyrinoids

According to the IUPAC definition,^[134] porphyrins are:

Natural pigments containing a fundamental skeleton of four pyrrole nuclei united through the α -positions by four methine groups to form a macrocyclic structure (porphyrin is designated porphine in Chemical Abstracts indexes).

The structure of a typical porphyrin is shown in Figure 1.14a. Four pyrrole rings and four methine carbons are linked together via bridges at the α -position of the pyrrole rings. Nonn’s nomenclature for expanded porphyrins was used to accurately describe the structural diversity of porphyrin derivatives.^[135] For example, in the case of [26]hexaphyrin(1.1.1.1.1.1) (Figure 1.14b), the first parentheses indicate the number of π electrons involved in the conjugation circuit. That is, [26]hexaphyrin has 26π electrons in the conjugation circuit. The middle part indicates the number of pyrroles comprising the expanded porphyrin. That is, “hexaphyrin” indicates that the macrocycle contains six pyrroles. Similarly, the middle part is used for pentaphyrin, heptaphyrin, and octaphyrin,

corresponding to five, seven, and eight pyrroles, respectively. The second parentheses indicate the number of methine carbons connecting adjacent pyrrole units. The hexaphyrin shown in Figure 1.14b is regularly ordered *meso*-aryl-substituted macrocycle; therefore, the last part should be (1.1.1.1.1.1).

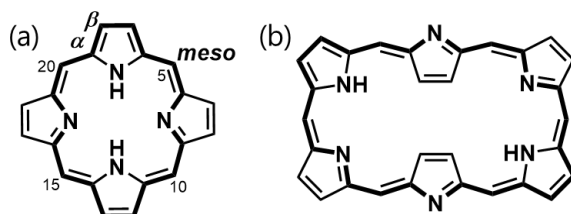


Figure 1.14 (a) Typical porphyrin structure. Counting starts at α -carbon as 1, β -carbon as 2, and *meso*-carbon as 5, as shown. (b) Structure of [26]hexaphyrin(1.1.1.1.1.1) as an example of Nonn's nomenclature.^[135]

Porphyrin derivatives possess a diverse range of structures that can be precisely modified by appropriate structural adjustments. One of the attractive strategies is modification of the porphyrin core by replacing one or two pyrrole rings with other heteroatom containing five-membered rings such as O, S, Se, Te, Si, P, and C; the resulting class of porphyrinoids are known as heteroatom-containing porphyrins or core-modified porphyrins (Figure 1.15a).^[136–139] The first core-modified porphyrins were synthesized in the 1970s by Broadhurst et al.^[140] Core-modified porphyrins absorb and emit light at lower energies depending on the number of substituted heteroatoms, making them excellent acceptors. Another advantage is their unique coordination chemistry. It has been established that core-modified porphyrins can stabilize metals in unusual oxidation states, such as Ni and Pd in the +1 oxidation state.^[141,142] Core-modified porphyrins, in which three or four pyrrole rings are replaced by heteroatoms, have also been reported, and they exhibit properties more similar to antiaromatic isophlorins than aromatic porphyrins (see Chapter 1.3.3).^[143,144]

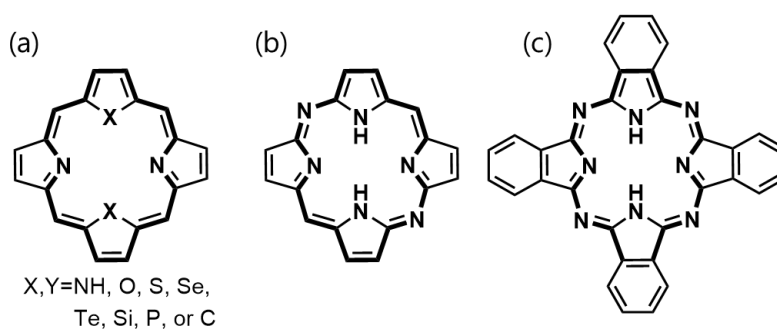


Figure 1.15 Structures of (a) core-modified porphyrins, (b) diazaporphyrin, a typical example of *meso*-heteroatom-substituted porphyrinoids, and (c) phthalocyanine.

Azaporphyrins are macrocyclic compounds in which one or more of the *meso*-carbons or β -

carbons are fully or partially replaced by nitrogen atoms, while still maintaining the 18π electron conjugation (Figure 1.15b). Additionally, *meso*-heteroatom-substituted porphyrinoids, which feature heteroatoms such as oxygen or sulfur within their structure, are also recognized.^[145,146] Due to the reduced molecular symmetry and electronic effects of the heteroatoms, they exhibit optical and electrochemical properties completely different from those of normal porphyrins. In the case of normal porphyrins, the four frontier orbitals, HOMO–1/HOMO and LUMO/LUMO+1, each orbitals are nearly degenerate. This describes the characteristic spectroscopic spectrum of porphyrins, as explained by the Gouterman four-orbital model.^[147–150] In azaporphyrins, these orbitals become partially or completely nondegenerate due to the reduced molecular symmetry. It is also well known that *meso*-hetero substitution lowers both the HOMO–1/HOMO and LUMO/LUMO+1 energy levels due to the larger electronegativity of nitrogen (3.04, Pauling units) compared to carbon (2.55). This difference therefore suggests that azaporphyrin π -systems are less susceptible to oxidation and more susceptible to reduction than porphyrins. According to this classification, phthalocyanines are considered to be tetrabenzo-fused 5,10,15,20-tetraazaporphyrins. Phthalocyanines are cyclic compounds with a structure in which four phthalimide units are bridged by nitrogen atoms (Figure 1.15c).^[146,151–155] Since Sir Reginald P. Linstead et al. clarified the structure and definition of the phthalocyanine molecule in 1933 and 1934,^[156] over forty phthalocyanine metal complexes, along with thousands of other phthalocyanine compounds, have been reported. Phthalocyanine is mostly used as a pigment due to its strong absorption of visible light, but is also used in electronic materials, cosmetics, and catalysts.

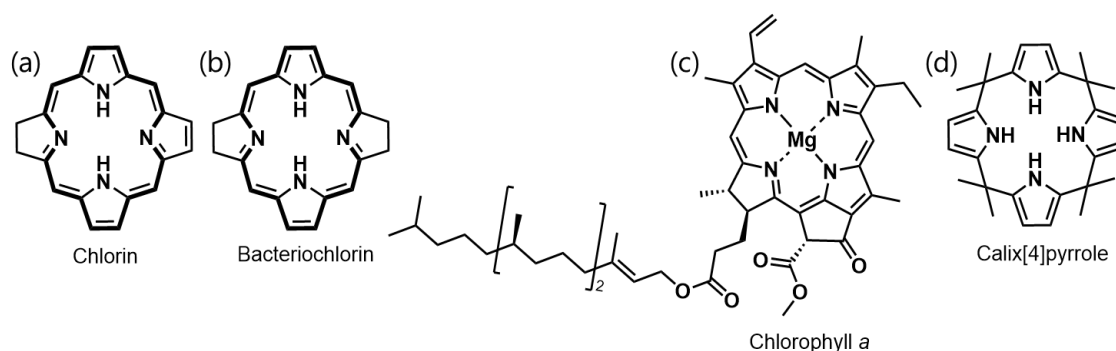


Figure 1.16 Structures of (a) chlorin, (b) bacteriochlorin, and (c) chlorophyll *a*. Chlorophyll *a* is the primary pigment involved in photosynthesis in organisms such as plants, algae, and cyanobacteria, playing a crucial role in transforming light energy into chemical energy. (d) Calix[4]pyrrole.

Chlorins and bacteriochlorins are hydrogenated porphyrin derivatives that exhibit longer wavelength absorption due to their lower molecular symmetry compared to porphyrins (Figures 1.16a, b).^[157] Chlorins are classified as 2,3-dihydroporphyrins, where one of the pyrrole rings in the porphyrin core has been reduced. In contrast, bacteriochlorins are 2,3,7,8-tetrahydroporphyrins, characterized by the reduction of two diagonal pyrrole rings. Various analogs of chlorins, such as mono-L-aspartyl

chlorin e6^[158] and *m*-tetrahydroxyphenyl chlorin (*m*THPC)^[159] are useful as photosensitizers in photodynamic therapy. The word “chlorin” is derived from chlorophyll, a photosynthetic pigment, the most prevalent source of chlorin (Figure 1.16c).

Calixpyrroles are characterized by a cyclic arrangement of pyrrole groups linked by *sp*₃-carbon atoms. Therefore, the individual pyrrole rings are not π -conjugated to each other. Calixpyrroles with various ring sizes have been reported,^[160–162] but the chemistry of calix[4]pyrroles consisting of four pyrrole units is much more developed than the thermodynamically unfavorable smaller or larger ring sizes.^[163–165] The discovery of calix[4]pyrroles dates to 1886, when von Bayer reported the acid-catalyzed condensation reaction of acetone with pyrrole (Figure 1.15d).^[166] Calixpyrroles have been utilized as strong anion receptors or ligands for transition and rare-earth metals.

Porphyrinoids of various sizes can be synthesized by changing the number of pyrrole rings and methine carbons. By replacing certain heteroatoms, a vast array of structures can be created. Porphyrinoid that consists of three pyrrole rings and three methine carbons is referred to as triphyrin(1.1.1) (= subporphyrin, Figure 1.17a).^[167–170] In 2006, Osuka et al. successfully synthesized boron(III) complex of aromatic tribenzosubporphin by using boric acid as a templating reagent to form the tripyrrole structure.^[171] While all previously reported subporphyrins are boron complexes with 14 π electron systems, Osuka et al. recently succeeded in synthesizing the first aromatic boron-free subporphyrin using a simple method different from previously explored strategies.^[172] Subphthalocyanine, which is a subporphyrin analog with three *meso* positions are substituted to nitrogen atoms, was discovered by chance by Mellor and Osco in 1972.^[173]

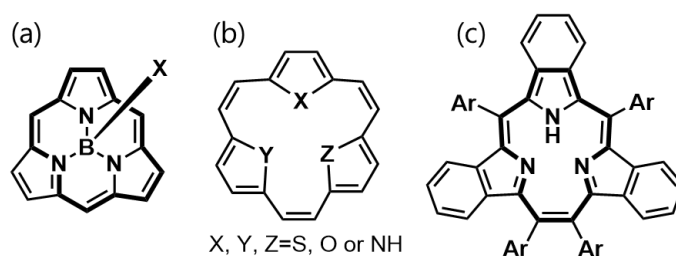


Figure 1.17 Structures of triphyrins. (a) First synthesized [14]subporphyrin,^[171] (b) first reported triphyrin analogs [18]triphyrin(2.2.2),^[168] and (c) second smallest triphyrin analogs, [14]triphyrin(2.1.1).^[175]

The structure of a methine-carbons-added subporphyrin is called triphyrin.^[168,174] The first triphyrins can be traced back to 1964, when Badger et al. reported so-called heteroatom-core-modified [18]annulenes ([18]triphyrin(2.2.2), Figure 1.17b). Smallest triphyrin is subporphyrin, and the second smallest triphyrin is [14]triphyrin(2.1.1), which first discovered by Kobayashi et al. during the synthesis of bicyclo[2.2.2]octadiene-fused porphyrins (Figure 1.17c).^[175]

[18]Tetraphyrin(1.1.1.0) (= corrole), is tetrapyrrolic 18π aromatic macrocycle that has direct pyrrole-pyrrole linkage and preserves the aromaticity of porphyrin despite having one less *meso*-carbon atom.^[176–179] Corroles have three ionizable protons and can stabilize metals in higher oxidation states than porphyrins. [18]Corrole was first synthesized by Johnson et al (Figure 1.18a).^[180] [16]Tetraphyrin(1.0.1.0) (= norcorrole), has a structure in which one *meso*-carbon is removed from corrole, and it possess 16π antiaromaticity (Figure 1.18b). The first report was by Kleeberg et al. in 2008.^[181] The next chapter will cover details of norcorrole.

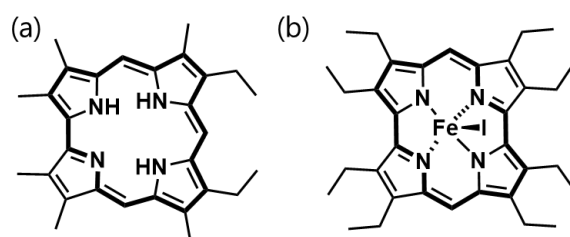


Figure 1.18 Structures of corrole and norcorrole. (a) First synthesized [18]corrole by Johnson et al.,^[180] and (b) first synthesized [16]norcorrole by Kleeberg et al.^[181]

Expanded porphyrins share many properties with traditional porphyrins, but they also possess unique characteristics and functions due to their flexible structures.^[182–185] The compounds have been extensively studied by research groups such as Woodward et al.,^[186] Franck and Nonn,^[135] Vogel et al.^[187] In 2001, a comprehensive series of synthetic methods for *meso*-pentafluorophenyl-substituted expanded porphyrins was reported by Osuka et al (Figure 1.19).^[188,189] These compounds feature a regular alternation of pyrrole and methine carbon atoms. Expanded porphyrins have been shown to exhibit a wide range of absorption bands from the visible to the near-infrared region, with high absorption coefficients. They display unique and interesting reactivity, including thermally induced rearrangements caused by exocyclic electronic interactions and skeletal rearrangements triggered by metal coordination. And, they have proven to be excellent platforms for the formation of stable aromatic and antiaromatic species, as well as conformationally twisted Möbius-shaped aromatic structures (Chapter 1.3.2).

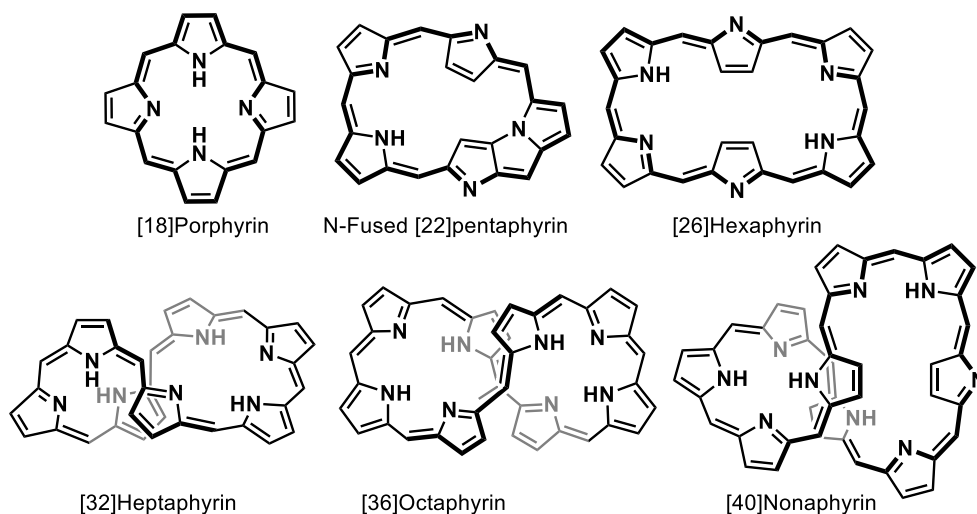


Figure 1.19 *Meso*-pentafluorophenyl-substituted porphyrin and expanded porphyrins. *Meso*-substituents are omitted for clarity.^[183]

The first synthesized porphyrin isomer was porphycene, [18]tetraphyrin(2.0.2.0) (Figure 1.20a).^[190] Porphycene is one of the most studied porphyrinoids because it is easy to synthesize, chemically stable, and exhibits excellent optical properties.^[191–194] Subsequently, alkyl-substituted derivatives of [18]tetraphyrin(2.1.0.1) (= corphycene)^[195] and [18]tetraphyrin(2.1.1.0) (= hemiporphycene) were obtained (Figure 1.20b, c). In 1999, metal complexes and derivatives of [18]tetraphyrin(3.1.0.1) (= isoporphycene)^[196] were successfully synthesized (Figure 1.20d). Other isomers, including [18]tetraphyrin(2.2.0.0), [18]tetraphyrin(3.1.0.0), and [18]tetraphyrin(4.0.0.0), can be considered, but they are highly unstable and considered not to be able to synthesize.^[197] Isomers with nitrogen atoms on the periphery of the macrocyclic ring are called 2-aza-21-carba[18]porphyrin, or “*N*-confused” or “mutant” porphyrins (Figure 1.20e).^[198,199] Singly *N*-confused porphyrin was reported in 1994 by two groups independently,^[200,201] and doubly *N*-confused porphyrin was synthesized in 2000 by Furuta et al. (Figure 1.20f).^[202] Confused porphyrins in which a nitrogen atom is located at the bridge between the pyrrole ring and the methine carbon are called neo-confused porphyrins (Figure 1.20g).^[203] The *N*-confused porphyrin skeleton is more flexible than that of the regular porphyrin, they easily induce the ring-inversion and fusion reaction. *N*-Fused porphyrins are the product of such a reaction (Figure 1.20h).^[204]

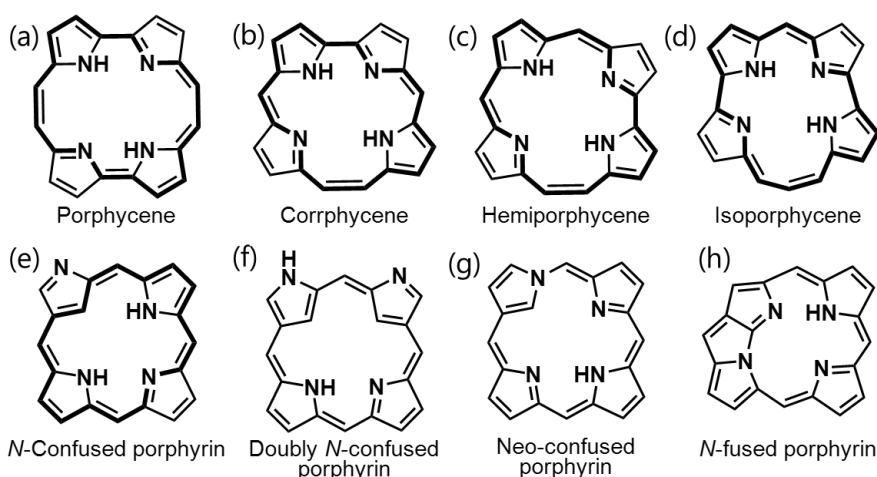


Figure 1.20 Structures of porphyrin isomers. The substituents are omitted for clarity.

By combining multiple porphyrin rings, novel physical properties can be obtained. Large metal centers that readily octacoordinate (e.g., rare earth elements, actinides, group 4 transition metals, and some typical elements such as In, Sn, As, Sb, and Bi) form porphyrin sandwich-like complexes with double-decker and triple-decker structures (Figures 1.21a, b).^[205–208] Due to the intramolecular π - π interactions and the unique properties of the metal centers, these novel complexes exhibit features not seen in non-sandwich complexes. They have garnered significant interest due to their distinctive absorption, redox, and magnetic properties, as well as the dynamic rotation of the porphyrin ligands.

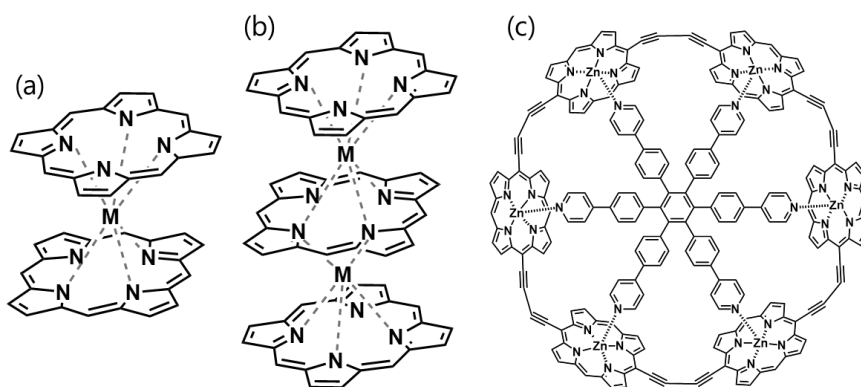


Figure 1.21 Structure of multi-porphyrin systems. (a) Porphyrin sandwich-like complex, double-decker and (b) triple-decker. (c) Porphyrin array reported by Anderson et al. that exhibits global aromaticity or global antiaromaticity via oxidizing/reducing the hole porphyrin nanoring.^[209]

There has been significant synthesis of porphyrin-linked macrocycles, which have attracted attention as mimics of the light-harvesting system in photosynthesis.^[210–212] Anderson et al. have observed global aromaticity, where multiple porphyrins are involved in conjugation, by oxidizing or reducing the porphyrin nano ring (Figure 1.21c).^[209,213–215] A more rigid structure can be obtained by linking the porphyrins at two β - and *meso*-positions.^[129,216]

As discussed in this chapter, porphyrinoids possess a macrocyclic π -conjugated structure, that gives them unique optical and electronic properties. These properties include strong absorption bands in the visible region. Additionally, their physical properties can be modified easily by metallation, making them valuable as functional materials. Regarding applied research using porphyrins, there are countless reports on catalysts^[217]—particularly for carbon dioxide reduction reactions^[218,219]—solar cells,^[220–222] dyes,^[223,224] and biological applications,^[130] especially photodynamic therapy.^[225–227] It is exciting to anticipate the synthesis of even more remarkable porphyrin derivatives and the discovery of new functions in the future.

1.4.2 Antiaromatic Porphyrinoids

Various types of porphyrinoids have been reported that possess not only aromaticity but also antiaromaticity. Examples of antiaromatic porphyrinoids include triphyrin, norcorrole, isophlorin, porphycene, orangarin, and hexaphyrin (Figure 1.22). Here $[4n]$ porphyrinoids are listed, which meets the requirements for Hückel antiaromaticity. It should be noted that not all compounds with $4n\pi$ electrons exhibit Hückel antiaromaticity. Depending on the shape of the molecule, it may exhibit Möbius aromaticity, and extremely distorted structures may require it to be treated as a nonaromatic compound even though they possess $4n\pi$ electrons.

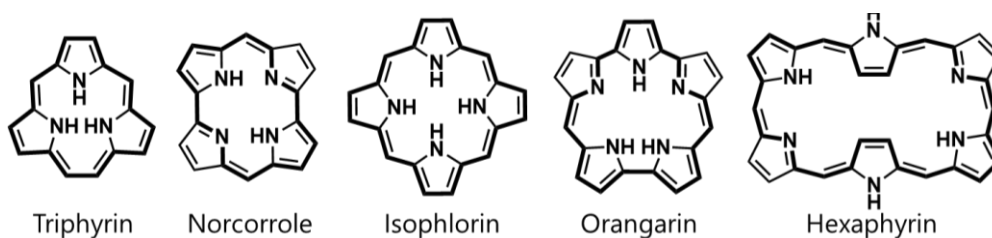


Figure 1.22 Examples of antiaromatic porphyrinoids. In addition to the compounds shown in this figure, the synthesis of many antiaromatic porphyrinoids has been reported.

Subporphyrin is the porphyrinoid composed of the fewest number of five-membered rings and methine carbons. To the best of the authors' knowledge, all experimentally isolated subporphyrins reported to date are aromatic compounds with a 14π electron system. The next smallest skeleton is triphyrin(2.1.1), which can be considered as a 14π aromatic form and its two-electron reduced, a 16π antiaromatic form. However, most reports so far have primarily concentrated on the 14π aromatic compound.^[168] The 16π antiaromatic form is difficult to synthesize because the inner NHs cause significant steric repulsion within the ring. Therefore, to obtain the 16π antiaromatic triphyrin, it is necessary to suppress the ring distortion caused by steric repulsion and maintain the molecular planarity. Examples include an antiaromatic $[16]$ triphyrin(2.1.1) analog with an aromatic ring fused triphyrin,^[228,229] a phosphorus-coordinated triphyrins where phosphorus coordinates to the nitrogen

atom of the pyrrole ring,^[230,231] and a heteroatom-core-modified triphyrin where the NH atom in the inner ring is replaced with an oxygen atom to reduce steric hindrance (Figure 1.23).^[232]

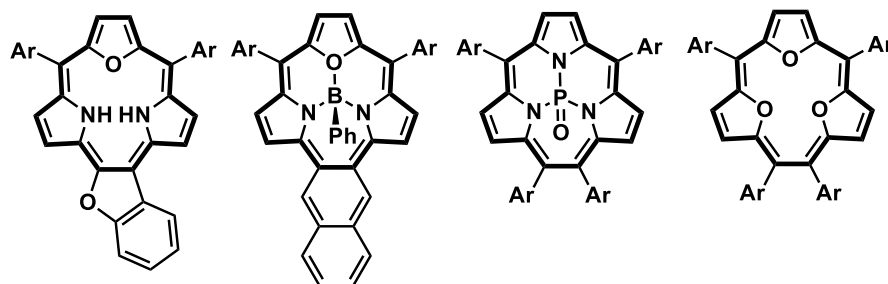


Figure 1.23 Structures of reported 16 π antiaromatic triphyrin(2.1.1)s.^[228–232]

[16]Norcorrole is another antiaromatic 16 π porphyrin analog. Research on norcorrole began in 2008 when Kleeberg et al. first succeeded in synthesizing it.^[181] Subsequently, Shinokubo et al. reported an easy gram-scale synthesis using a nickel as a template (Figure 1.24a).^[233] They are highly stable and can be used as antiaromatic moieties, including investigation into its electrical conductivity properties,^[114] demonstration of the theory of stacked-ring aromaticity (Figure 1.24b),^[61,234] and realization of molecular cage containing six norcorrole rings with a highly paratropic cavity.^[235] Recently, a phthalocyanine derivative of norcorrole was reported (Figure 1.24c).^[236] Unlike the structural diversity found in porphyrin derivatives, phthalocyanine derivatives—which are widely used in materials and life sciences—have been constrained by the absence of a versatile synthetic method. However, this paper presents a new synthetic approach that addresses this limitation.

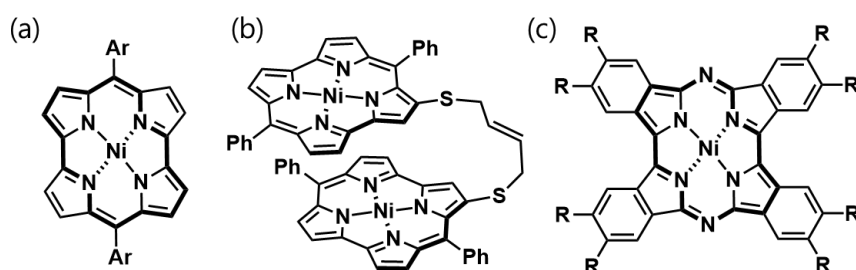


Figure 1.24 Structures of norcorroles. (a) The first reported gram-scale synthesis by Shinokubo et al.^[233] (b) Molecular structure used to demonstrate the theory of stacked-ring aromaticity.^[234] (c) A phthalocyanine derivative of norcorrole.^[236]

Several examples of [16]corrole with antiaromatic properties have also been reported.^[237–239] In 2021, Osuka et al. reported the 16 π antiaromatic corrole cation (Figure 1.25a).^[237] Another type of 16 π electron antiaromatic porphyrinoid is [16]porphyrin, which are two-electron oxidized forms of porphyrins. The first reported 16 π porphyrin by Yamamoto et al. in 2005 had a distorted structure and exhibited nonaromatic property,^[240] but in 2006, Cissell et al. reported a 16 π porphyrin lithium

complex with antiaromaticity (Figure 1.25b).^[241] In addition, in 2020, Halder et al. reported the synthesis of a 16 π confused porphyrin (Figure 1.25c).^[242]

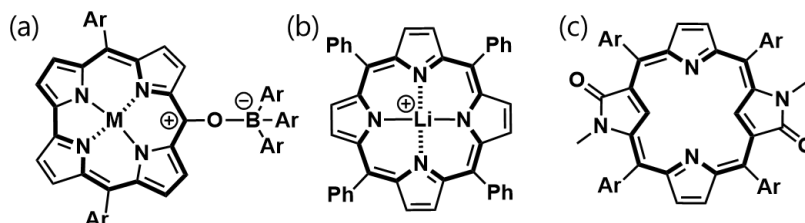


Figure 1.25 Structures of 16 π antiaromatic porphyrinoids. (a) First antiaromatic [16]corrole reported by Osuka et al.^[237] (b) Antiaromatic 16 π antiaromatic porphyrin, synthesized via 2-electron oxidation of porphyrin.^[241] (c) *N*-confused 16 π antiaromatic porphyrin.^[242]

20 π Electron antiaromatic porphyrinoids include [20]tetraphyrin(1.1.1.1) (= isophlorin), which is a two-electron reduced form of the porphyrin itself; *meso*-heteroatom-substituted porphyrin derivatives; [20]porphycene, which means an isomer of [20]isophlorin; and confused porphyrin derivatives. Isophlorin is discussed in detail in Chapter 1.3.3. Regarding *meso*-heteroatom-substituted porphyrin derivatives, Matano et al. synthesized a stable *meso*-diazaporphyrin containing nitrogen atoms at the 5th and 15th positions (Figure 1.26a).^[243]

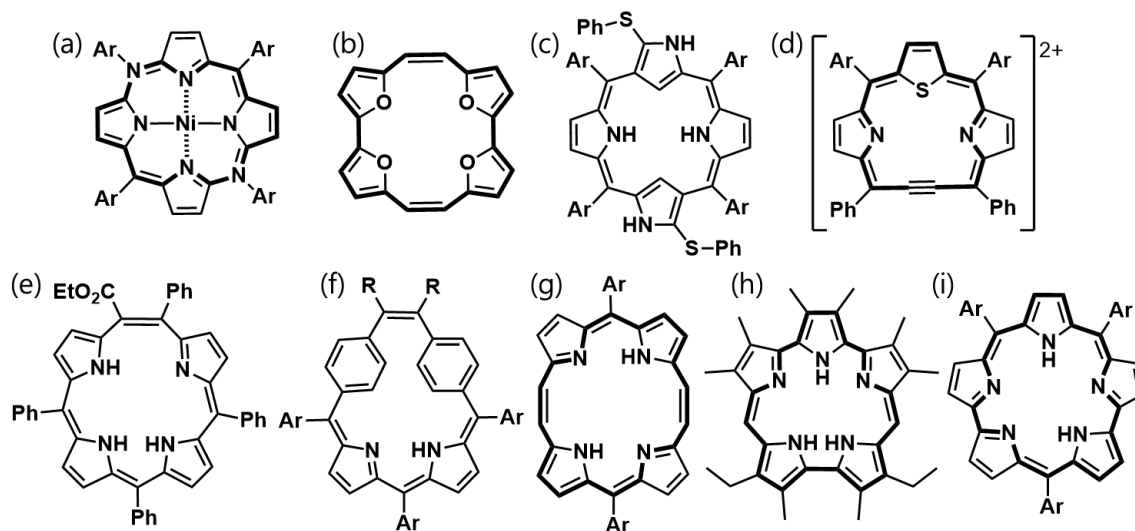


Figure 1.26 Structures of 20 π antiaromatic porphyrinoids. (a) 5,15-Diazaporphyrin,^[243] (b) core-modified tetraoxa-porphycene,^[247] (c) doubly *N*-confused porphyrin,^[248] (d) ethine-bridged porphyrin derivative,^[249] (e) [20]homoporphyrin(2.1.1.1),^[250] (f) [20]carbaporphyrinoids, the analog of homoporphyrin,^[251] (g) antiaromatic vinylogous porphyrins, [20]tetraphyrin(2.1.2.1),^[252] (h) [20]orangarin,^[253] and (i) [20]smaragdyrin.^[254]

This molecule is substituted with nitrogen atoms at two *meso*-positions in porphyrin, making it a 20π antiaromatic compound in the neutral state. One-electron-oxidized 19π radical cations and two-electrons-oxidized 18π aromatic dication have also been stably isolated. *Meso*-dioxo-,^[244] *meso*-dithia-,^[245] *meso*-aza-oxa-,^[246] and *meso*-azathiaporphyrins were also reported, all of them exhibited antiaromaticity, except for dithia-analogs.

Antiaromatic [20]porphycene was reported by Vogel et al. in 1988, which has a core-modified-tetraoxa structure (Figure 1.26b).^[247] A non-core-modified porphycene was also synthesized, but it had a distorted structure and exhibited nonaromaticity.^[247] Several antiaromatic confused porphyrins are reported, including the doubly-*N*-confused porphyrin (Figure 1.26c),^[248] mono-*S*-confused tetrathiaporphyrin,^[255] and mono-*Te*-confused telluriumporphyrin.^[256] Also, Latos-Grażyński et al. reported ethine-bridged porphyrin isomer dication with weak antiaromaticity (Figure 1.26d).^[249]

Another type of 20π antiaromatic porphyrinoid is ring expanded porphyrin analogs. [20]Tetraphyrin(2.1.1.1) (= homoporphyrin) is a kind of expanded porphyrin analog. The first 20π electron homoporphyrin was reported in 1975 (Figure 1.26e),^[250] and although synthesis studies have continued since then, it has been reported that nonaromatic forms can be obtained even with heteroatom-core-modification.^[257,258] Srinivasan et al., reported the smallest Möbius aromatic homoporphyrin with 20π electrons.^[259] Srinivasan et al. also reported the first carbaporphyrinoids analogue of homoporphyrin by introducing terphenyl systems in the macrocyclic core (Figure 1.26f).^[251] Almost all reported carbaporphyrinoids so far are nonaromatic, including Srinivasan's report.^[260,261] Porphyrin(2.1.2.1) (= Vinylogous porphyrins,) is also the kind of 20π antiaromatic porphyrinoids. In 2006, Andriolette et al. reported the first nonaromatic [20]porphyrin(2.1.2.1),^[262] followed by the antiaromatic one reported by Osuka et al. (Figure 1.26g)^[252] Recently Helten et al. reported the antiaromatic *meso*-dibora [20]porphyrin(2.1.2.1).^[263] [20]Pentaphyrin(1.0.1.0.0) (= orangarin) is the smallest pentapyrrolic 20π porphyrinoid system reported to date and it was named orangarin due to its bright orange color (Figure 1.26h).^[253] Pentaphyrin(1.1.0.1.0) (= smaragdyrin) is a historic but elusive pentapyrrolic macrocycle. Osuka et al. synthesized [20]smaragdyrin by oxidizing the BF_3 -complex of [22]smaragdyrin as a stable antiaromatic compound (Figure 1.26i).^[254] Smaragdyrin comes from the Latin word "*Smaragdus*" from its intense green color.

As for 24π electron porphyrinoid, in 1995, Sessler et al. reported a nonaromatic [24]hexaphyrin(1.1.0.1.1.0) (= amethyrin) (Figure 1.27a), along with the synthesis of [20]orangarin, using hexaalkyl tetrapyrrole as a building block.^[253] Shimizu et al. reported [24]hexaphyrin(1.1.0.1.1.0) (= rubyrin) with antiaromatic character, whose name originates from the Latin "*Rubeus*" (Figure 1.27b).^[264] Core-modified 24π electron antiaromatic porphyrinoid was synthesized by Anand et al., using pentathia-[24]pentaphyrin(1.1.1.1.1) cation and pentathia-[24]pentaphyrin(1.1.1.1.0) (= sapphyrin) (Figure 1.27c).^[265,266]

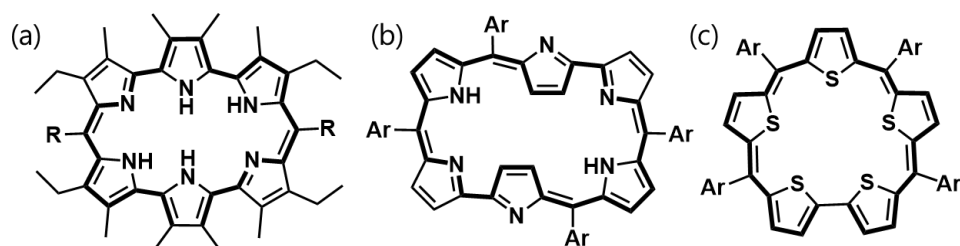


Figure 1.27 Structures of 24π electronic porphyrinoids. (a) [24]Amethyrin,^[253] (b) [24]ruberin,^[264] and (c) pentathia-[24]sapphyrin.^[266]

In 2005, Osuka et al. reported the 28π electronic porphyrinoid, by two electron reduction of [26]hexaphyrin(1.1.1.1.1.1) Ni(II), Pd(II), and Pt(II) complexes (Figure 1.28a).^[267] They found that [28]hexaphyrin(1.1.1.1.1.1) divalent metal complexes took a twisted conformation to provide a cavity to accommodate a divalent metal ion. These complexes were recognized as Möbius aromatic with 28π electrons in 2008,^[268] after the first experimental report of Möbius aromatic compounds by Helges et al.^[40] Metal-free [28]hexaphyrin(1.1.1.1.1.1) was first synthesized by Drew et al. in 1999, but the ^1H NMR spectra was considered a mystery for a long time.^[269] Osuka et al. solved this mystery by considering a rapid interconverting conformational dynamics among a planar Hückel antiaromatic conformation and several twisted Möbius aromatic conformations (Figure 1.28b).^[270] They developed this explanation after analyzing the crystal structures of several Möbius aromatic conformers of [28]hexaphyrin(1.1.1.1.1.1); the crystal structures of metal-free [28]hexaphyrin(1.1.1.1.1.1) depended upon the crystallization solvents. The crystal structure of gold(III) complex of [28]hexaphyrin(1.1.1.1.1.1) exhibited the planar structure (Figure 1.28c), showing the antiaromaticity confirmed by ^1H NMR.^[271] [28]Hexaphyrin(1.1.1.1.1.1) with bulky substituents like halogen atom or phenyl groups showed the figure-eight conformation (Figure 1.28d), with weak aromatic character.^[272,273] Moreover, protonation of [28]hexaphyrin(1.1.1.1.1.1) with methanesulfonic acid (MSA) afforded the triangular-shape with Hückel antiaromaticity (Figure 1.28e).^[273] Monophosphorus [28]hexaphyrin(1.1.1.1.1.1) exhibited Möbius aromaticity whereas bisphosphorus [30]hexaphyrin(1.1.1.1.1.1) exhibited Möbius antiaromaticity (Figure 1.28f).^[274]

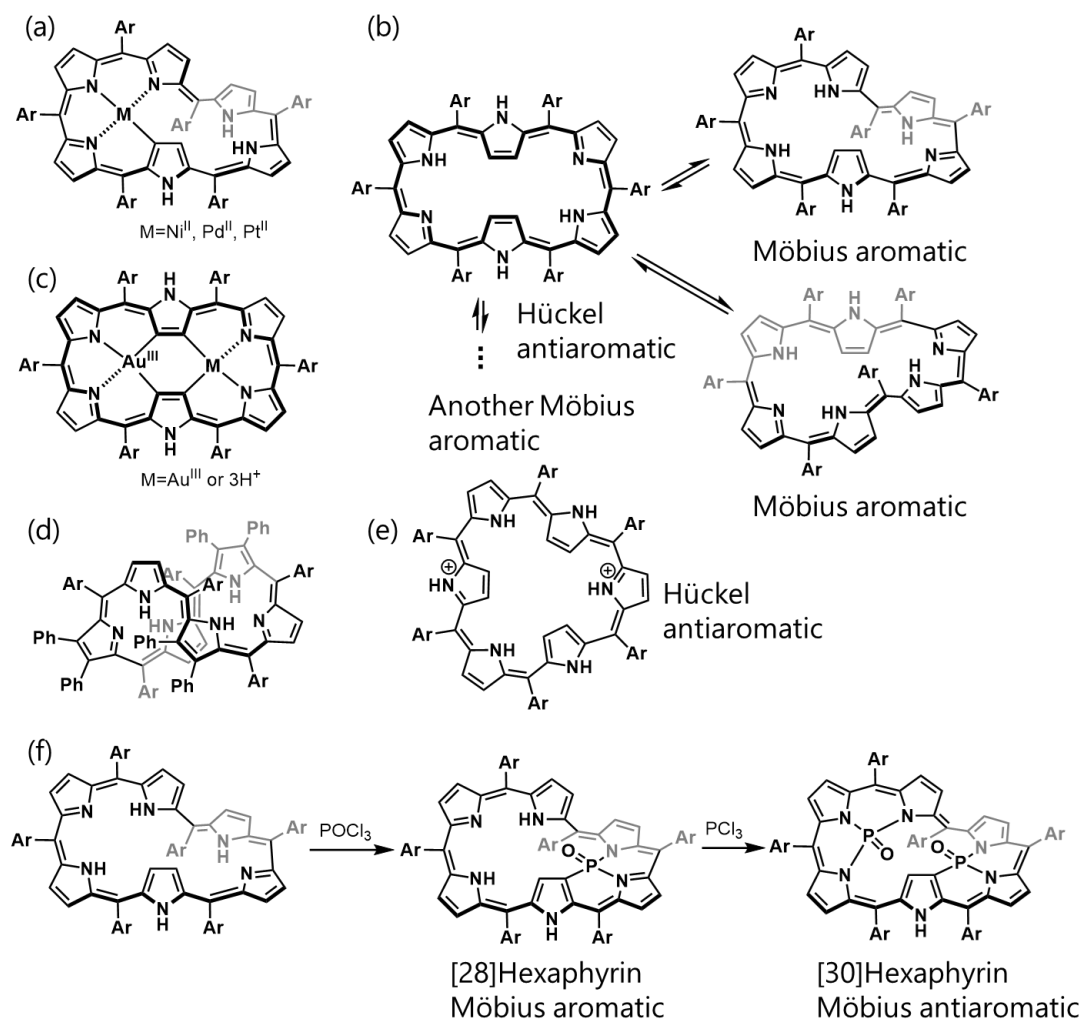


Figure 1.28 Various conformational and aromaticity changes of [28]hexaphyrin(1.1.1.1.1.1). (a) Divalent metal complex with Möbius aromaticity.^[164] (b) A metal-free [28]hexaphyrin(1.1.1.1.1.1) with a planar Hückel antiaromatic and several twisted Möbius aromatic conformations.^[270] (c) Gold(III) complexes with Hückel antiaromaticity.^[271] (d) Figure-eight conformation via bulky substitution.^[273] (e) Protonation afford the triangular-shape with Hückel antiaromaticity.^[273] (f) Möbius aromatic [28]hexaphyrin(1.1.1.1.1.1) monophosphorous complex and Möbius antiaromatic [30]hexaphyrin(1.1.1.1.1.1) bisphosphorus complex.^[274]

As 28 π electronic heptaphyrin analogs, [28]heptaphyrin(1.0.0.1.0.0.0) was synthesized by Sessler et al. in 1999 (Figure 1.29a),^[275] and strong antiaromatic [28]heptaphyrin(1.1.0.0.1.0.0) by Osuka et al. in 2024 (Figure 1.29b).^[276]

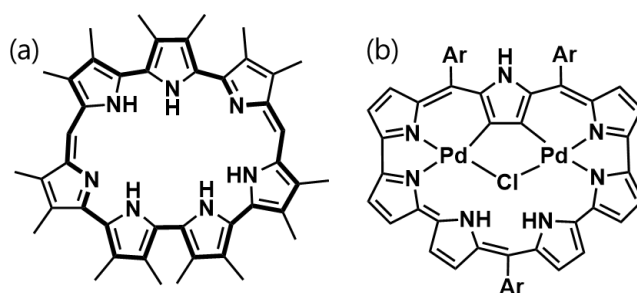


Figure 1.29 (a) [28]Heptaphyrin(1.0.0.1.0.0.0),^[275] and (b) [28]heptaphyrin(1.1.0.0.1.0.0).^[276]

[32]Heptaphyrin(1.1.1.1.1.1.1) inherently possess one porphyrin-like tetrapyrrolic cavities, with which these expanded porphyrins accommodated one divalent metal ions to form [32]heptaphyrin mono-metal(II) complex quantitatively.^[277] These complexes showed twisted figure-eight conformations in the solid state, and when they treated with BBr_3 and MeOH, they split into [14]subporphyrin boron complex and [18]porphyrin metal complex (Figure 1.30a).^[278] Protonation of [32]heptaphyrin(1.1.1.1.1.1.1) with trifluoroacetic acid (TFA) allowed the formation of several protonated species, one of which was revealed to be a Möbius aromatic monoprotinated [32]heptaphyrin.^[279] Metal-free [32]heptaphyrin displayed structural transitions depending on solvent polarity, leading to either Hückel or Möbius topologies (Figure 1.30b).^[280] In nonpolar solvents like toluene, the Hückel antiaromatic form was predominant, but in polar solvents such as THF, Möbius aromaticity was predominant.

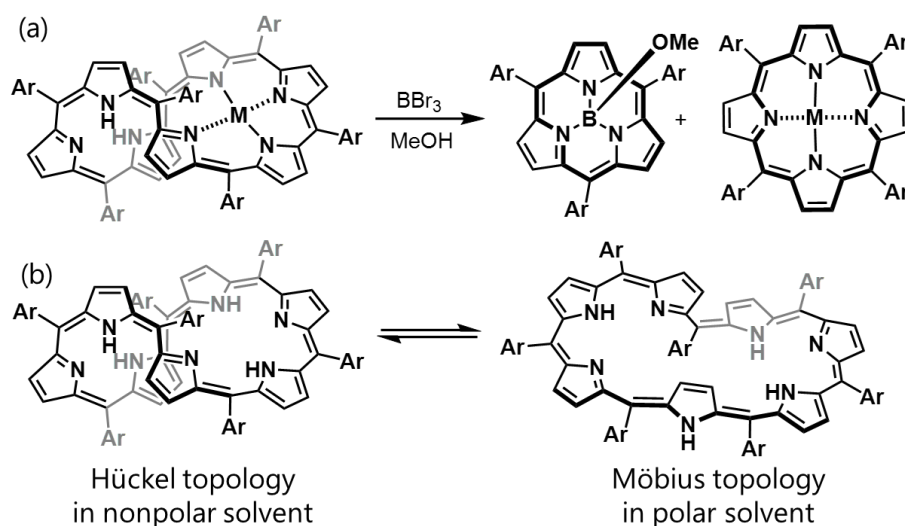


Figure 1.30 Structure of [32]heptaphyrin(1.1.1.1.1.1.1). (a) Splitting reaction into [14]subporphyrin and [18]porphyrin, identical to [32]heptaphyrin(1.1.1.1.1.1.1),^[278] and (b) solvent effect on conformational change.^[280]

Thiophene-fused core-modified [32]heptaphyrin was reported by Chandrashekar et al (Figure 1.31a).^[281] [32]Octaphyrin(1.0.0.0.1.0.0.0) was synthesized by Sessler et al., using

quaterpyrroles as building blocks along with [28]heptaphyrin(1.0.0.1.0.0.0) (Figure 1.31b).^[275] Antiaromatic [32]octaphyrin(1.0.1.0.1.0.1.0) di-Pd(II) complex by Shinokubo et al. (Figure 1.31c)^[282] using the same precursor as norcorrole synthesis.^[233]

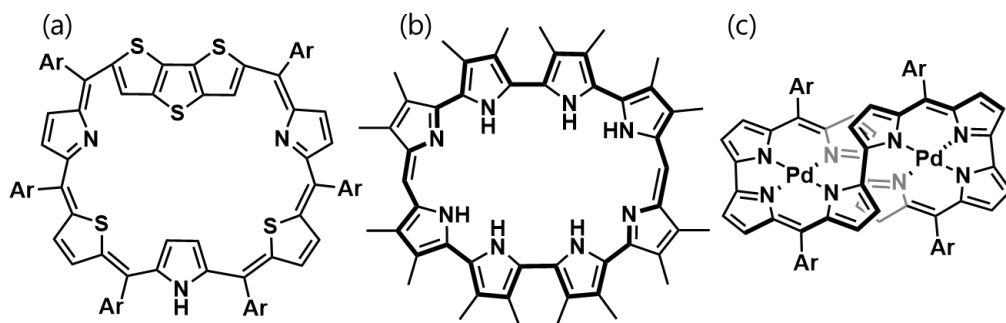


Figure 1.31 Structures of 32 π porphyrinoids, except for [32]heptaphyrin(1.1.1.1.1.1.1). (a) Thiophene-fused core-modified [32]heptaphyrin,^[281] (b) [32]octaphyrin(1.0.0.0.1.0.0.0),^[275] and (c) [32]octaphyrin(1.0.1.0.1.0.1.0) di-Pd(II) complex.^[282]

[36]Octaphyrin(1.1.1.1.1.1.1.1) has the figure-eight structure and it was nonaromatic molecule.^[283] It splits thermally into corresponding two [18]porphyrin(1.1.1.1). It is known that metal-free [36]octaphyrin(1.1.1.1.1.1.1.1) exhibits the rearrangement reaction via Ni(II) inserting reaction, resulting in the formation of the *meso-meso* spiro-linked dimer via *meso*-carboxylation (Figure 1.32a)^[284,285] or the *meso- β* linked [18]porphyrin dimer (Figure 1.32b).^[286]

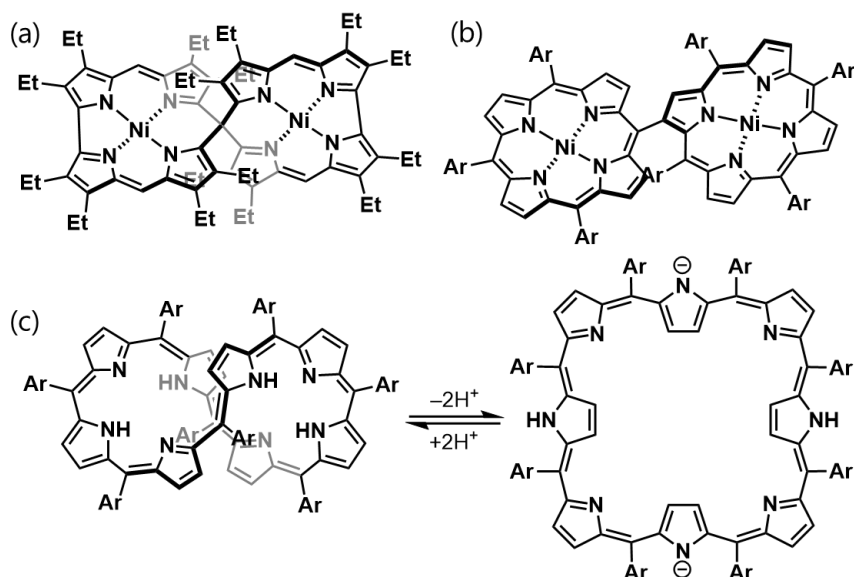


Figure 1.32 Structures of compounds derived from [36]octaphyrin(1.1.1.1.1.1.1.1) via (a) Ni(II) inserting reaction, resulting in the formation of the *meso-meso* spiro-linked dimer via *meso*-carboxylation ^[284,285] or (b) the *meso- β* linked [18]porphyrin(1.1.1.1) dimer.^[286] (c) Deprotonation induces the planarization.

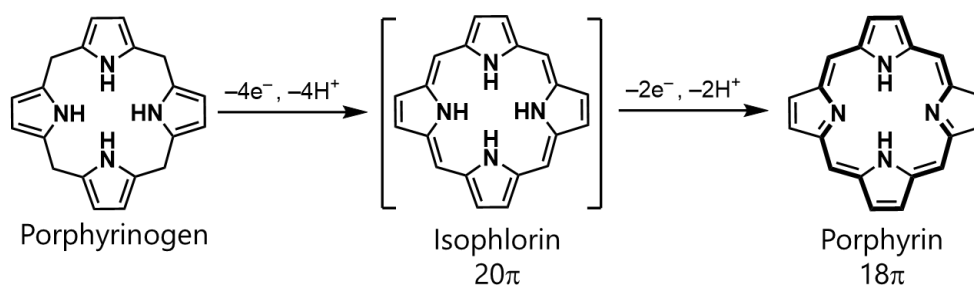
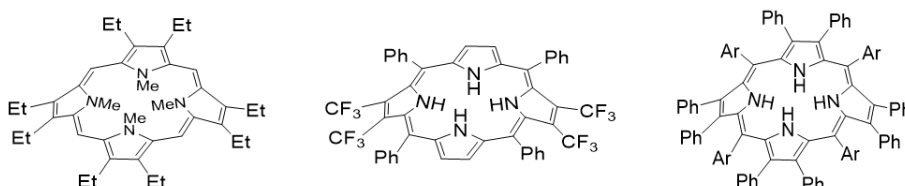


Figure 1.33 Porphyrin synthetic method proposed by Woodward.



Therefore, two approaches were devised to synthesize isophlorin that maintains planarity without losing antiaromaticity. The first approach was introducing a bridging structure into the central cavity of the ring (Figure 1.35a),^[300–303] or by incorporating tetravalent metals such as Si^{IV} or Ge^{IV} (Figure 1.35b).^[304–306] The isophlorins exhibited a planar structure and antiaromaticity but are highly unstable and cannot be handled under atmospheric conditions. The second approach involves replacing the central nitrogen atoms with heteroatoms such as oxygen or sulfur to prevent steric hindrance of the inner NHs (Figure 1.35c). Except for tetrathiaisophlorin,^[307] which possesses four sulfur atoms at the center and loses planarity due to steric hindrance, all other isophlorin derivatives exhibited pronounced antiaromaticity.^[143,144,308]

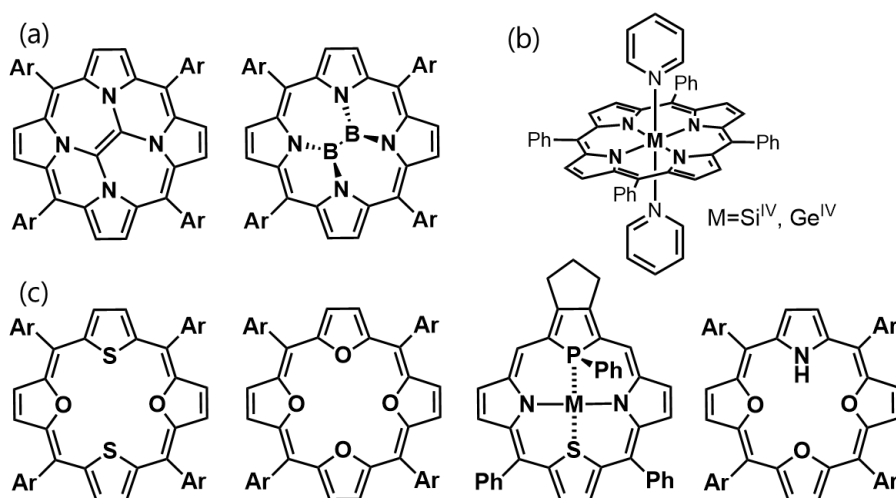


Figure 1.35 Structures of antiaromatic isophlorins and their derivatives. (a) Isophlorins with a bridging structure into the central cavity of the ring.^[300–303] (b) Isophlorin metal complexes of tetravalent metals such as Si^{IV} or Ge^{IV} .^[304–306] (c) Heteroatom-substituted isophlorin derivatives.^[143,144,308]

All heteroatom-substituted isophlorin derivatives exhibit antiaromaticity. Particularly heteroatom-substituted isophlorin derivatives bearing electron-withdrawing substituents are stable under atmospheric conditions and display strong antiaromaticity. This occurs because the heteroatom substitution blocks the conjugation pathway of the 18π electron system, which passes through the heteroatom. Blocking the 18π electron conjugation pathway destabilizes porphyrins, relatively stabilizing the 20π electron system of isophlorins.^[309] Thus, while heteroatom substitution enables the synthesis of planar, stable antiaromatic isophlorin derivatives, nitrogen-containing isophlorins are generally difficult to synthesize. Synthetic reports of antiaromatic isophlorin derivatives bearing two or more nitrogen atoms are limited to only two examples: a weakly antiaromatic isophlorin where two nitrogen atoms are substituted by phosphorus and sulfur,^[308] and an antiaromatic isophlorin where two nitrogen atoms are substituted by sulfur atoms.^[310] Thus, the synthesis of antiaromatic isophlorins with few nitrogen substitutions remains a challenging task that requires further research.

1.5 Summary and Prospects

This chapter began with a historical overview of aromatic and antiaromatic compounds, introduced theoretical concepts, and explored their synthesis and applications. The chemistry of aromatic and antiaromatic compounds dates to Faraday's isolation of benzene, two hundred years ago, and has continued to be a prominent focus in organic chemistry ever since. Experiments have revealed that aromatic compounds, such as benzene, are highly stable and react unusually with halogens, etc. Quantum chemical approaches are necessary to explain their stability. The electron counting rule has been particularly useful for determining whether a compound is aromatic or antiaromatic, and,

consequently, its physical properties. Furthermore, the concept of aromaticity continues to evolve to encompass different types of stability, such as Hückel aromaticity, Möbius aromaticity, excited-state aromaticity, three-dimensional aromaticity, and stacked-ring aromaticity. The aromatic stabilization effect is now believed to be a superposition of multiple phenomena and should be considered from energetic, geometric, magnetic and electronic perspectives. Indicators for defining aromaticity and antiaromaticity have also been established, enabling the aromaticity and antiaromaticity of compounds to be examined from both experimental and theoretical perspectives. Many experimental chemists synthesize a variety of compounds and use “aromaticity” to describe their properties. However, some theoretical chemists are warning that the term “aromaticity” has become so widespread that various physical phenomena are being explained simply by this term. Although “aromaticity” is a useful term for describing the stability and physical properties of compounds, experimental chemists should consider the aromaticity and antiaromaticity of compounds, for example, from molecular orbital perspectives, rather than basing their judgements on a single experimental result. Similarly, theoretical chemists must consider experimental findings while ensuring they are not overly constrained by theoretical frameworks. In recent years, experimental chemists have started conducting theoretical calculations, and vice versa, leading to active interdisciplinary discussions. Experimental and theoretical research are expected to advance in tandem and become more closely connected.

This chapter also introduced porphyrin, a well-known aromatic compound. Porphyrinoids are aromatic cyclic conjugated compounds consisting of four five-membered rings containing nitrogen atoms that are linked by methine carbons. By modifying their structure, a wide variety of porphyrinoids have been synthesized, revealing a wide range of properties. Porphyrinoids are recognized for their capacity to synthesize stable antiaromatic compounds. Various antiaromatic porphyrinoids have been synthesized through ring expansion and heteroatom substitution, resulting from advances in organic chemistry, including the development of diverse reactions. Various porphyrinoids extend beyond the classical Hückel aromatic and antiaromatic framework, including Möbius aromaticity, excited-state aromaticity, and stacked-ring aromaticity. Woodward, winner of the Nobel Prize in Chemistry for his work on the total synthesis of natural porphyrin derivatives such as vitamin B12, has indicated the existence of isophlorin. Isophlorin can be produced by reducing porphyrin by two electrons. However, synthesis of the isophlorin skeleton itself has yet to be reported, suggesting that further advancements in porphyrin chemistry are still possible.

Considering these factors, this thesis focuses on synthesizing a stable antiaromatic isophlorin containing four nitrogen atoms in its core. A comparison of the properties of porphyrin and isophlorin illustrates the differences between aromaticity and antiaromaticity. This thesis also investigates isophlorin metal complexes and core-modified isophlorin analogs with various substituents. Synthesizing and analyzing the physical properties of antiaromatic isophlorins and their analogs clarifies the correlation between the structure and physical properties of antiaromatic

compounds. These findings will provide guidelines for designing future antiaromatic compounds. The findings of this thesis pave the way for the synthesis of antiaromatic isophlorin and contribute to the development of numerous antiaromatic compounds. These compounds have a unique electronic structure that can be utilized in applied research to create new functional materials.

1.6 References

- [1] I. Fernández, Ed. , *Aromaticity: Modern Computational Methods and Applications*, Elsevier, **2021**.
- [2] M. Solà, A. I. Boldyrev, M. K. Cyrański, T. M. Krygowski, G. Merino, Ed. , *Aromaticity and Antiaromaticity: Concepts and Applications*, John Wiley & Sons, **2022**.
- [3] P. R. Schleyer, *Chem. Rev.* **2001**, *101*, 1115–1118.
- [4] R. Hoffmann, *J. Am. Chem. Sci.* **2015**, *103*, 18.
- [5] M. Francel, *Nat. Chem.* **2015**, *7*, 6–7.
- [6] A. J. Roche, *Angew. Chem. Int. Ed Engl.* **2015**, *54*, 46–50.
- [7] M. Faraday, *Philos. Trans. R. Soc. Lond.* **1825**, *115*, 440–466.
- [8] E. Mitscherlich, *Ann. Pharm.* **1834**, *9*, 39–48.
- [9] A. W. Hofmann, *Proc. R. Soc. Lond.* **1857**, *8*, 1–3.
- [10] A. Kekulé, *Bulletin mensuel de la Société Chimique de Paris* **1865**.
- [11] J. C. Slater, *Phys. Rev.* **1931**, *37*, 481–489.
- [12] L. Pauling, *The Nature of the Chemical Bond and the Structure of Molecules and Crystals: An Introduction to Modern Structural Chemistry*, Cornell University Press, Ithaca, New York, **1960**.
- [13] L. Pauling, G. W. Wheland, *J. Chem. Phys.* **1933**, *1*, 362–374.
- [14] Z. B. Q. B., zum Problem Q. B., *Z. Phys. Chem* **1931**, *70*, 204–286.
- [15] E. Hückel, *Eur. Phys. J. A* **1931**, *72*, 310–337.
- [16] E. Hückel, *Eur. Phys. J. A* **1932**, *76*, 628–648.
- [17] E. Hückel, *Eur. Phys. J. A* **1933**, *83*, 632–668.
- [18] W. von E. Doering, F. L. Detert, *J. Am. Chem. Soc.* **1951**, *73*, 876–877.
- [19] M. Solà, *Nat. Chem.* **2022**, *14*, 585–590.
- [20] G. Merino, M. Solà, I. Fernández, C. Foroutan-Nejad, P. Lazzeretti, G. Frenking, H. L. Anderson, D. Sundholm, F. P. Cossío, M. A. Petrukhina, J. Wu, J. I. Wu, A. Restrepo, *Chem. Sci.* **2023**, *14*, 5569–5576.
- [21] A. L. Chung, M. J. Dewar, *J. Chem. Phys.* **1965**, *42*, 756–766.
- [22] R. Breslow, *Angew. Chem. Int. Ed. Engl.* **1968**, *7*, 565–570.
- [23] R. Breslow, *Acc. Chem. Res.* **1973**, *6*, 393–398.
- [24] M. K. Cyrański, *Chem. Rev.* **2005**, *105*, 3773–3811.
- [25] T. M. Krygowski, H. Szatyłowicz, O. A. Stasyuk, J. Dominikowska, M. Palusiak, *Chem. Rev.*

2014, *114*, 6383–6422.

- [26] R. Gershoni-Poranne, A. Stanger, *Chem. Soc. Rev.* **2015**, *44*, 6597–6615.
- [27] F. Feixas, E. Matito, J. Poater, M. Solà, *Chem. Soc. Rev.* **2015**, *44*, 6434–6451.
- [28] F. De Proft, P. Geerlings, *Chem. Rev.* **2001**, *101*, 1451–1464.
- [29] I. Alkorta, J. Elguero, *New J. Chem.* **1999**, *23*, 951–954.
- [30] M. K. Cyrański, T. M. Krygowski, A. R. Katritzky, P. von R. Schleyer, *J. Org. Chem.* **2002**, *67*, 1333–1338.
- [31] M. Solà, *Front. Chem.* **2017**, *5*, 22.
- [32] L. Van Duong, H. T. Pham, N. M. Tam, M. T. Nguyen, *Phys. Chem. Chem. Phys.* **2014**, *16*, 19470–19478.
- [33] M. Rosenberg, C. Dahlstrand, K. Kilså, H. Ottosson, *Chem. Rev.* **2014**, *114*, 5379–5425.
- [34] M. Solà, *Wiley Interdiscip. Rev. Comput. Mol. Sci.* **2019**, *9*, e1404.
- [35] A. A. Frost, B. Musulin, *J. Chem. Phys.* **1953**, *21*, 572–573.
- [36] W. Von E. Doering, L. H. Knox, *J. Am. Chem. Soc.* **1954**, *76*, 3203–3206.
- [37] R. Breslow, B. Jaun, R. Q. Kluttz, C.-Z. Xia, *Tetrahedron* **1982**, *38*, 863–867.
- [38] D. P. Craig, N. L. Paddock, *Nature* **1958**, *181*, 1052–1053.
- [39] E. Heilbronner, *Tetrahedron Lett.* **1964**, *5*, 1923–1928.
- [40] D. Ajami, O. Oeckler, A. Simon, R. Herges, *Nature* **2003**, *426*, 819–821.
- [41] C. Castro, Z. Chen, C. S. Wannere, H. Jiao, W. L. Karney, M. Mauksch, R. Puchta, N. J. R. van E. Hommes, P. von R. Schleyer, *J. Am. Chem. Soc.* **2005**, *127*, 2425–2432.
- [42] M. Stepień, L. Latos-Grazyński, N. Sprutta, P. Chwalisz, L. Szterenberg, *Angew. Chem. Int. Ed Engl.* **2007**, *46*, 7869–7873.
- [43] M. Mauksch, S. B. Tsogoeva, *Chem. Eur. J.* **2010**, *16*, 7843–7851.
- [44] N. C. Baird, *J. Am. Chem. Soc.* **1972**, *94*, 4941–4948.
- [45] H. Ottosson, *Nature Chemistry* **2012**, *4*, 969–971.
- [46] P. Wan, E. Krogh, *J. Chem. Soc. Chem. Commun.* **1985**, *0*, 1207.
- [47] P. B. Karadakov, *J. Phys. Chem. A* **2008**, *112*, 12707–12713.
- [48] P. B. Karadakov, *J. Phys. Chem. A* **2008**, *112*, 7303–7309.
- [49] D. Shukla, P. Wan, *J. Am. Chem. Soc.* **1993**, *115*, 2990–2991.
- [50] G. Portella, J. Poater, J. M. Bofill, P. Alemany, M. Solà, *J. Org. Chem.* **2005**, *70*, 2509–2521.
- [51] A. Hirsch, Z. Chen, H. Jiao, *Angew. Chem. Int. Ed Engl.* **2000**, *39*, 3915–3917.
- [52] M. Bühl, A. Hirsch, *Chem. Rev.* **2001**, *101*, 1153–1183.
- [53] J. Poater, M. Solà, *Chem. Commun.* **2011**, *47*, 11647–11649.
- [54] Z. Chen, H. Jiao, A. Hirsch, P. von Ragué Schleyer, *Angew. Chem. Weinheim Bergstr. Ger.* **2002**, *114*, 4485–4488.
- [55] Z. Chen, R. B. King, *Chem. Rev.* **2005**, *105*, 3613–3642.

- [56] C. R. Martinez, B. L. Iverson, *Chem. Sci.* **2012**, *3*, 2191.
- [57] D. J. Cram, J. M. Cram, *Acc. Chem. Res.* **1971**, *4*, 204–213.
- [58] P. G. Ghasemabadi, T. Yao, G. J. Bodwell, *Chem. Soc. Rev.* **2015**, *44*, 6494–6518.
- [59] C. Corminboeuf, P. von R. Schleyer, P. Warner, *Org. Lett.* **2007**, *9*, 3263–3266.
- [60] J.-I. Aihara, *J. Phys. Chem. A* **2009**, *113*, 7945–7952.
- [61] R. Nozawa, J. Kim, J. Oh, A. Lamping, Y. Wang, S. Shimizu, I. Hisaki, T. Kowalczyk, H. Fliegl, D. Kim, H. Shinokubo, *Nat. Commun.* **2019**, *10*, 3576.
- [62] P. R. von Schleyer, H. Jiao, *Pure Appl. Chem.* **1996**, *68*, 209–218.
- [63] H. Ottosson, *Chem. Sci.* **2023**, *14*, 5542–5544.
- [64] M. Baranac-Stojanović, *Chemistry* **2025**, *7*, 127.
- [65] S. W. Slayden, J. F. Liebman, *Chem. Rev.* **2001**, *101*, 1541–1566.
- [66] J. Kruszewski, T. M. Krygowski, *Tetrahedron Lett.* **1972**, *13*, 3839–3842.
- [67] I. Casademont-Reig, E. Ramos-Cordoba, M. Torrent-Sucarrat, E. Matito, *Molecules* **2020**, *25*, 711.
- [68] P. von R. Schleyer, C. Maerker, A. Dransfeld, H. Jiao, N. J. R. van Eikema Hommes, *J. Am. Chem. Soc.* **1996**, *118*, 6317–6318.
- [69] Z. Chen, C. S. Wannere, C. Corminboeuf, R. Puchta, P. von R. Schleyer, *Chem. Rev.* **2005**, *105*, 3842–3888.
- [70] P. J. Mayer, H. Ottosson, *J. Phys. Org. Chem.* **2025**, *38*, e70000.
- [71] D. Geuenich, K. Hess, F. Köhler, R. Herges, *Chem. Rev.* **2005**, *105*, 3758–3772.
- [72] H. Fliegl, S. Taubert, O. Lehtonen, D. Sundholm, *Phys. Chem. Chem. Phys.* **2011**, *13*, 20500–20518.
- [73] M. Giambiagi, M. S. de Giambiagi, C. D. dos Santos Silva, A. P. de Figueiredo, *Phys. Chem. Chem. Phys.* **2000**, *2*, 3381–3392.
- [74] E. Matito, M. Duran, M. Solà, *J. Chem. Phys.* **2005**, *122*, 14109.
- [75] E. Matito, M. Solà, P. Salvador, M. Duran, *Faraday Discuss.* **2007**, *135*, 325–345.
- [76] P. Bultinck, R. Ponec, S. Van Damme, *J. Phys. Org. Chem.* **2005**, *18*, 706–718.
- [77] E. Matito, *Phys. Chem. Chem. Phys.* **2016**, *18*, 11839–11846.
- [78] I. Casademont-Reig, T. Woller, J. Contreras-García, M. Alonso, M. Torrent-Sucarrat, E. Matito, *Phys. Chem. Chem. Phys.* **2018**, *20*, 2787–2796.
- [79] R. Gleiter, G. Haberhauser, *Aromaticity and Other Conjugation Effect*, Wiley-VCH, Weinheim, Germany, **2012**.
- [80] Q. Zhu, S. Chen, D. Chen, L. Lin, K. Xiao, L. Zhao, M. Solà, J. Zhu, *Fundam. Res.* **2023**, *3*, 926–938.
- [81] R. Lavendomme, M. Yamashina, *Chem. Sci.* **2024**, *15*, 18677–18697.
- [82] M. Jirásek, M. Rickhaus, L. Tejerina, H. L. Anderson, *J. Am. Chem. Soc.* **2021**, *143*, 2403–2412.

- [83] M. J. S. Dewar, G. J. Gleicher, *J. Am. Chem. Soc.* **1965**, *87*, 692–696.
- [84] M. J. S. Dewar, C. De Llano, *J. Am. Chem. Soc.* **1969**, *91*, 789–795.
- [85] L. Van Nyvel, M. Alonso, M. Solà, *Chem. Sci.* **2025**, *16*, 5613–5622.
- [86] A. Kekulé, *Justus Liebigs Ann. Chem.* **1872**, *162*, 77–124.
- [87] H. Kimling, A. Krebs, *Angew. Chem., Int. Ed. Engl.* **1972**, *11*, 932–933.
- [88] G. Maier, S. Pfriem, U. Schäfer, R. Matusch, *Angew. Chem., Int. Ed. Engl.* **1978**, *17*, 520–521.
- [89] D. J. Cram, M. E. Tanner, R. Thomas, *Angew. Chem., Int. Ed. Engl.* **1991**, *30*, 1024–1027.
- [90] R. Willstätter, E. Waser, *Ber. Dtsch. Chem. Ges.* **1911**, *44*, 3423–3445.
- [91] F.-G. Klärner, *Angew. Chem. Int. Ed Engl.* **2001**, *40*, 3977–3981.
- [92] T. Nishinaga, T. Ohmae, M. Iyoda, *Symmetry (Basel)* **2010**, *2*, 76–97.
- [93] R. L. Soulen, S. K. Choi, J. D. Park, *J. Fluor. Chem.* **1973**, *3*, 141–150.
- [94] F. W. B. Einstein, A. C. Willis, W. R. Cullen, R. L. Soulen, *J. Chem. Soc., Chem. Commun.* **1981**, 526–528.
- [95] K. K. Baldrige, J. S. Siegel, *J. Am. Chem. Soc.* **2001**, *123*, 1755–1759.
- [96] T. Ohmae, T. Nishinaga, M. Wu, M. Iyoda, *J. Am. Chem. Soc.* **2010**, *132*, 1066–1074.
- [97] Y. Nakamura, N. Aratani, K. Furukawa, A. Osuka, *Tetrahedron* **2008**, *64*, 11433–11439.
- [98] Y. Nakamura, N. Aratani, H. Shinokubo, A. Takagi, T. Kawai, T. Matsumoto, Z. S. Yoon, D. Y. Kim, T. K. Ahn, D. Kim, A. Muranaka, N. Kobayashi, A. Osuka, *J. Am. Chem. Soc.* **2006**, *128*, 4119–4127.
- [99] K. Hafner, K. H. Häfner, C. König, M. Kreuder, G. Ploss, G. Schulz, E. Sturm, K. H. Vöpel, *Angew. Chem., Int. Ed. Engl.* **1963**, *2*, 123–134.
- [100] K. Hafner, H. U. Süss, *Angew. Chem., Int. Ed. Engl.* **1973**, *12*, 575–577.
- [101] B. Kitschke, H. J. Lindner, *Tetrahedron Lett.* **1977**, *18*, 2511–2514.
- [102] K. Brand, *Ber. Dtsch. Chem. Ges.* **1912**, *45*, 3071–3077.
- [103] T. Kawase, J.-I. Nishida, *Chem. Rec.* **2015**, *15*, 1045–1059.
- [104] A. Konishi, Y. Okada, M. Nakano, K. Sugisaki, K. Sato, T. Takui, M. Yasuda, *J. Am. Chem. Soc.* **2017**, *139*, 15284–15287.
- [105] D. Wassy, M. Pfeifer, B. Esser, *J. Org. Chem.* **2020**, *85*, 34–43.
- [106] J. Sprachmann, T. Wachsmuth, M. Bhosale, D. Burmeister, G. J. Smales, M. Schmidt, Z. Kochovski, N. Grabicki, R. Wessling, E. J. W. List-Kratochvil, B. Esser, O. Dumele, *J. Am. Chem. Soc.* **2023**, *145*, 2840–2851.
- [107] M. Nakano, I. Osaka, K. Takimiya, T. Koganezawa, *Journal of Materials Chemistry C* **2014**, *2*, 64–70.
- [108] K. Hafner, B. Stowasser, H.-P. Krimmer, S. Fischer, M. C. Böhm, H. J. Lindner, *Angew. Chem., Int. Ed. Engl.* **1986**, *25*, 630–632.
- [109] D. T. Chase, A. G. Fix, B. D. Rose, C. D. Weber, S. Nobusue, C. E. Stockwell, Haley M., *Angew.*

- Chem. Int. Ed.* **2011**, *50*, 11103–11106.
- [110] F. Sondheimer, *Acc. Chem. Res.* **1972**, *5*, 81–91.
- [111] R. Breslow, S. T. Schneebeli, *Tetrahedron* **2011**, *67*, 10171–10178.
- [112] W. Chen, H. Li, J. R. Widawsky, C. Appayee, L. Venkataraman, R. Breslow, *J. Am. Chem. Soc.* **2014**, *136*, 918–920.
- [113] A. Mahendran, P. Gopinath, R. Breslow, *Tetrahedron Lett.* **2015**, *56*, 4833–4835.
- [114] S. Fujii, S. Marqués-González, J.-Y. Shin, H. Shinokubo, T. Masuda, T. Nishino, N. P. Arasu, H. Vázquez, M. Kiguchi, *Nat. Commun.* **2017**, *8*, 15984.
- [115] G. Dai, J. Chang, X. Shi, W. Zhang, B. Zheng, K.-W. Huang, C. Chi, *Chem. Eur. J.* **2015**, *21*, 2019–2028.
- [116] G. Dai, J. Chang, W. Zhang, S. Bai, K.-W. Huang, J. Xu, C. Chi, *Chem. Commun. (Camb.)* **2015**, *51*, 503–506.
- [117] Z. Jin, Z.-F. Yao, K. P. Barker, J. Pei, Y. Xia, *Angew. Chem. Int. Ed.* **2019**, *58*, 2034–2039.
- [118] Z. Zhang, H. Fan, X. Zhu, *Org. Chem. Front.* **2017**, *4*, 711–716.
- [119] F. Glöcklhofer, *Open Res. Eur.* **2025**, *5*, 70.
- [120] H. Koike, M. Chikamatsu, R. Azumi, J. Tsutsumi, K. Ogawa, W. Yamane, T. Nishiuchi, T. Kubo, T. Hasegawa, K. Kanai, *Adv. Funct. Mater.* **2016**, *26*, 277–283.
- [121] Y. Tullimilli, W. Zeng, X. Lu, J. Wu, *Chem. Commun.* **2018**, *54*, 2186–2199.
- [122] O. El Bakouri, J. R. Smith, H. Ottosson, *J. Am. Chem. Soc.* **2020**, *142*, 5602–5617.
- [123] K. Wang, X. You, X. Miao, Y. Yi, S. Peng, D. Wu, X. Chen, J. Xu, M. Y. Sfeir, J. Xia, *J. Am. Chem. Soc.* **2024**, *146*, 13326–13335.
- [124] C. Yuan, S. Saito, C. Camacho, S. Irle, I. Hisaki, S. Yamaguchi, *J. Am. Chem. Soc.* **2013**, *135*, 8842–8845.
- [125] H. Kim, W. Park, Y. Kim, M. Filatov, C. H. Choi, D. Lee, *Nat. Commun.* **2021**, *12*, 5409.
- [126] H. Kim, Y. Kim, D. Lee, *Acc. Chem. Res.* **2023**, *57*, 140–152.
- [127] P. Krzyszowska, E. Pacholska-Dudziak, *Nat. Chem.* **2025**, *17*, 156.
- [128] A. Ghosh, *The Porphyrin Handbook*, Academic Press, San Diego, CA, **2000**.
- [129] T. Tanaka, A. Osuka, *Chem. Soc. Rev.* **2015**, *44*, 943–969.
- [130] J. M. Park, K.-I. Hong, H. Lee, W.-D. Jang, *Acc. Chem. Res.* **2021**, *54*, 2249–2260.
- [131] Y. Shi, F. Zhang, R. J. Linhardt, *Dyes Pigm.* **2021**, *188*, 109136.
- [132] W. Küster, *Physiol. Chemie* **1912**, *82*, 463–483.
- [133] H. Fischer, *Sci. Nat.* **1929**, *17*, 611–617.
- [134] International Union of Pure and Applied Chemistry, “porphyrins” in *IUPAC Compendium of Chemical Terminology*, 5th Ed, **2025**.
- [135] B. Franck, A. Nonn, *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 1795–1811.
- [136] P. J. Chmielewski, L. Latos-Grażyński, *Coord. Chem. Rev.* **2005**, *249*, 2510–2533.

- [137] I. Gupta, M. Ravikanth, *Coord. Chem. Rev.* **2006**, *250*, 468–518.
- [138] B. Szyszko, L. Latos-Grażyński, *Chem. Soc. Rev.* **2015**, *44*, 3588–3616.
- [139] T. Chatterjee, V. S. Shetti, R. Sharma, M. Ravikanth, *Chem. Rev.* **2017**, *117*, 3254–3328.
- [140] M. J. Broadhurst, R. Grigg, A. W. Johnson, *J. Chem. Soc. D* **1969**, 1480–1482.
- [141] P. Chmielewski, M. Grzeszczuk, L. Latos-Grazynski, J. Lisowski, *Inorg. Chem.* **1989**, *28*, 3546–3552.
- [142] L. Latos-Grazynski, J. Lisowski, P. Chmielewski, M. Grzeszczuk, M. M. Olmstead, A. L. Balch, *Inorg. Chem.* **1994**, *33*, 192–197.
- [143] S. P. Panchal, S. C. Gadekar, V. G. Anand, *Angew. Chem. Int. Ed Engl.* **2016**, *55*, 7797–7800.
- [144] J. S. Reddy, V. G. Anand, *J. Am. Chem. Soc.* **2008**, *130*, 3718–3719.
- [145] P. A. Stuzhin, O. G. Khelevina, *Coord. Chem. Rev.* **1996**, *147*, 41–86.
- [146] J. Mack, N. Kobayashi, *Chem. Rev.* **2011**, *111*, 281–321.
- [147] M. Gouterman, *J. Mol. Spectrosc.* **1961**, *6*, 138–163.
- [148] M. Gouterman, G. H. Wagnière, L. C. Snyder, *J. Mol. Spectrosc.* **1963**, *11*, 108–127.
- [149] C. Weiss, H. Kobayashi, M. Gouterman, *J. Mol. Spectrosc.* **1965**, *16*, 415–450.
- [150] H. Du, M. Taniguchi, J. R. Diers, C. Kirmaier, D. F. Bocian, J. S. Lindsey, D. Holten, *Photochem. Photobiol.* **2025**, *101*, 869–885.
- [151] G. de la Torre, P. Vázquez, F. Agulló-López, T. Torres, *Chem. Rev.* **2004**, *104*, 3723–3750.
- [152] C. G. Claessens, U. Hahn, T. Torres, *Chem. Rec.* **2008**, *8*, 75–97.
- [153] A. B. Sorokin, *Chem. Rev.* **2013**, *113*, 8152–8191.
- [154] H. Lu, N. Kobayashi, *Chem. Rev.* **2016**, *116*, 6184–6261.
- [155] X. Li, X.-H. Peng, B.-D. Zheng, J. Tang, Y. Zhao, B.-Y. Zheng, M.-R. Ke, J.-D. Huang, *Chem. Sci.* **2018**, *9*, 2098–2104.
- [156] R. P. Linstead, *J. Chem. Soc.* **1934**, 1016.
- [157] P. Pallavi, K. Harini, V. Anand Arumugam, P. Gowtham, K. Girigoswami, S. Muthukrishnan, A. Girigoswami, *Evid. Based. Complement. Alternat. Med.* **2022**, *2022*, 3011918.
- [158] A. Hak, M. S. Ali, S. A. Sankaranarayanan, V. R. Shinde, A. K. Rengan, *ACS Appl. Bio Mater.* **2023**, *6*, 349–364.
- [159] M. O. Senge, J. C. Brandt, *Photochem. Photobiol.* **2011**, *87*, 1240–1296.
- [160] D. S. Kim, J. L. Sessler, *Chem. Soc. Rev.* **2015**, *44*, 532–546.
- [161] S. Peng, Q. He, G. I. Vargas-Zúñiga, L. Qin, I. Hwang, S. K. Kim, N. J. Heo, C.-H. Lee, R. Dutta, J. L. Sessler, *Chem. Soc. Rev.* **2020**, *49*, 865–907.
- [162] I. A. Rather, R. Ali, A. Ali, *Org. Chem. Front.* **2022**, *9*, 6416–6440.
- [163] J. L. Sessler, P. Anzenbacher Jr, J. A. Shriver, K. Jursíková, V. M. Lynch, M. Marquez, *J. Am. Chem. Soc.* **2000**, *122*, 12061–12062.
- [164] G. Cafeo, F. H. Kohnke, G. L. La Torre, M. F. Parisi, R. Pistone Nascone, A. J. P. White, D. J.

- Williams, *Chem. Eur. J.* **2002**, *8*, 3148.
- [165] Y. Inaba, Y. Nomata, Y. Ide, J. Pirillo, Y. Hijikata, T. Yoneda, A. Osuka, J. L. Sessler, Y. Inokuma, *J. Am. Chem. Soc.* **2021**, *143*, 12355–12360.
- [166] A. Baeyer, *Ber. Dtsch. Chem. Ges.* **1886**, *19*, 2184–2185.
- [167] C. G. Claessens, D. González-Rodríguez, M. S. Rodríguez-Morgade, A. Medina, T. Torres, *Chem. Rev.* **2014**, *114*, 2192–2277.
- [168] S. Shimizu, *Chem. Rev.* **2017**, *117*, 2730–2784.
- [169] S. Shimizu, *Angew. Chem. Int. Ed.* **2023**, e202217099.
- [170] Z. Li, Q. Gong, E. Hao, L. Jiao, *Coord. Chem. Rev.* **2023**, *493*, 215325.
- [171] Y. Inokuma, J. H. Kwon, T. K. Ahn, M.-C. Yoo, D. Kim, A. Osuka, *Angew. Chem. Int. Ed.* **2006**, *45*, 961–964.
- [172] L. Liu, J. Kim, L. Xu, Y. Rao, M. Zhou, B. Yin, J. Oh, D. Kim, A. Osuka, J. Song, *Angew. Chem. Int. Ed.* **2022**, *61*, e202214342.
- [173] A. Meller, A. Ossko, *Monatsh. Chem.* **1972**, *103*, 150–155.
- [174] D. Prasannan, M. Ravikanth, *Coord. Chem. Rev.* **2020**, *407*, 213172.
- [175] Z.-L. Xue, Z. Shen, J. Mack, D. Kuzuhara, H. Yamada, T. Okujima, N. Ono, X.-Z. You, N. Kobayashi, *J. Am. Chem. Soc.* **2008**, *130*, 16478–16479.
- [176] I. Aviv, Z. Gross, *Chem. Commun.* **2007**, 1987–1999.
- [177] R. Orłowski, D. Gryko, D. T. Gryko, *Chem. Rev.* **2017**, *117*, 3102–3137.
- [178] A. Ghosh, *Chem. Rev.* **2017**, *117*, 3798–3881.
- [179] J. F. B. Barata, M. G. P. M. S. Neves, M. A. F. Faustino, A. C. Tomé, J. A. S. Cavaleiro, *Chem. Rev.* **2017**, *117*, 3192–3253.
- [180] A. W. Johnson, I. T. Kay, *J. Chem. Soc.* **1965**, 1620.
- [181] M. Bröring, S. Köhler, C. Kleeberg, *Angew. Chem. Int. Ed.* **2008**, *47*, 5658–5660.
- [182] S. Saito, A. Osuka, *Angew. Chem. Int. Ed.* **2011**, *50*, 4342–4373.
- [183] A. Osuka, S. Saito, *Chem. Commun.* **2011**, *47*, 4330.
- [184] B. Szyszko, M. J. Białek, E. Pacholska-Dudziak, L. Latos-Grażyński, *Chem. Rev.* **2017**, *117*, 2839–2909.
- [185] T. Tanaka, A. Osuka, *Chem. Rev.* **2017**, *117*, 2584–2640.
- [186] V. J. Bauer, D. L. J. Clive, D. Dolphin, J. B. Paine III, F. L. Harris, M. M. King, J. Loder, S. W. C. Wang, R. B. Woodward, *J. Am. Chem. Soc.* **1983**, *105*, 6429–6436.
- [187] E. Vogel, *J. Heterocycl. Chem.* **1996**, *33*, 1461–1487.
- [188] J.-Y. Shin, H. Furuta, K. Yoza, S. Igarashi, A. Osuka, *J. Am. Chem. Soc.* **2001**, *123*, 7190–7191.
- [189] J.-Y. Shin, H. Furuta, A. Osuka, *Angew. Chem. Int. Ed.* **2001**, *40*, 619–621.
- [190] E. Vogel, M. Köcher, H. Schmickler, J. Lex, *Angew. Chem., Int. Ed. Engl.* **1986**, *25*, 257–259.
- [191] S. E. Braslavsky, M. Müller, D. O. Mártire, S. Pörting, S. G. Bertolotti, S. Chakravorti, G. Koç-

- Weier, B. Knipp, K. Schaffner, *J. Photochem. Photobiol. B* **1997**, *40*, 191–198.
- [192] D. Sánchez-García, J. L. Sessler, *Chem. Soc. Rev.* **2008**, *37*, 215–232.
- [193] G. Anguera, D. Sánchez-García, *Chem. Rev.* **2017**, *117*, 2481–2516.
- [194] J. Waluk, *Chem. Rev.* **2017**, *117*, 2447–2480.
- [195] J. L. Sessler, E. A. Brucker, S. J. Weghorn, M. Kisters, M. Schäfer, J. Lex, E. Vogel, *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 2308–2312.
- [196] E. Vogel, M. Bröring, C. Erben, R. Demuth, J. Lex, M. Nendel, K. N. Houk, *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 353–357.
- [197] Y.-D. Wu, K. W. K. Chan, C.-P. Yip, E. Vogel, D. A. Plattner, K. N. Houk, *J. Org. Chem.* **1997**, *62*, 9240–9250.
- [198] M. Toganoh, H. Furuta, *Chem. Lett.* **2019**, *48*, 615–622.
- [199] M. Toganoh, H. Furuta, *Chem. Rev.* **2022**, *122*, 8313–8437.
- [200] H. Furuta, T. Asano, T. Ogawa, *J. Am. Chem. Soc.* **1994**, *116*, 767–768.
- [201] P. J. Chmielewski, L. Latos-Grażyński, K. Rachlewicz, T. Glowiak, *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 779–781.
- [202] H. Furuta, H. Maeda, A. Osuka, *J. Am. Chem. Soc.* **2000**, *122*, 803–807.
- [203] P. Pushpanandan, M. Ravikanth, *Top. Curr. Chem. (J)* **2021**, *379*, 26.
- [204] H. Furuta, T. Ishizuka, A. Osuka, T. Ogawa, *J. Am. Chem. Soc.* **1999**, *121*, 2945–2946.
- [205] D. K. P. Ng, J. Jiang, *Chemical Society Reviews* **1997**, *26*, 433–442.
- [206] J. Jiang, D. K. P. Ng, *Acc. Chem. Res.* **2009**, *42*, 79–88.
- [207] H. Wang, B.-W. Wang, Y. Bian, S. Gao, J. Jiang, *Coord. Chem. Rev.* **2016**, *306*, 195–216.
- [208] A. G. Martynov, Y. Horii, K. Katoh, Y. Bian, J. Jiang, M. Yamashita, Y. G. Gorbunova, *Chem. Soc. Rev.* **2022**, *51*, 9262–9339.
- [209] M. D. Peeks, T. D. W. Claridge, H. L. Anderson, *Nature* **2017**, *541*, 200–203.
- [210] A. K. Burrell, D. L. Officer, P. G. Plieger, D. C. Reid, *Chem. Rev.* **2001**, *101*, 2751–2796.
- [211] D. Kim, A. Osuka, *Acc. Chem. Res.* **2004**, *37*, 735–745.
- [212] N. Aratani, D. Kim, A. Osuka, *Acc. Chem. Res.* **2009**, *42*, 1922–1934.
- [213] M. Rickhaus, M. Jirasek, L. Tejerina, H. Gotfredsen, M. D. Peeks, R. Haver, H.-W. Jiang, T. D. W. Claridge, H. L. Anderson, *Nat. Chem.* **2020**, *12*, 236–241.
- [214] J. M. Holmes, H. Gotfredsen, L. Gödde, J. Hergenbahn, K. Rani, K. E. Yamada, J.-R. Deng, L. Warwick, M. Clarke, M. Edmondson, J. N. O’Shea, A. Saywell, H. L. Anderson, *J. Am. Chem. Soc.* **2025**, *147*, 32840–32850.
- [215] M. Jirásek, H. L. Anderson, M. D. Peeks, *Acc. Chem. Res.* **2021**, *54*, 3241–3251.
- [216] A. Osuka, T. Tanaka, *Chem. Eur. J.* **2018**, *24*, 17188–17200.
- [217] L. Feng, K.-Y. Wang, E. Joseph, H.-C. Zhou, *Trends Chem.* **2020**, *2*, 555–568.
- [218] C. Costentin, M. Robert, J.-M. Savéant, *Acc. Chem. Res.* **2015**, *48*, 2996–3006.

- [219] Z. Liang, H.-Y. Wang, H. Zheng, W. Zhang, R. Cao, *Chem. Soc. Rev.* **2021**, *50*, 2540–2581.
- [220] W. M. Campbell, A. K. Burrell, D. L. Officer, K. W. Jolley, *Coord. Chem. Rev.* **2004**, *248*, 1363–1379.
- [221] L.-L. Li, E. W.-G. Diau, *Chem. Soc. Rev.* **2013**, *42*, 291–304.
- [222] M. Urbani, M. Grätzel, M. K. Nazeeruddin, T. Torres, *Chem. Rev.* **2014**, *114*, 12330–12396.
- [223] M. Pawlicki, H. A. Collins, R. G. Denning, H. L. Anderson, *Angew. Chem. Int. Ed.* **2009**, *48*, 3244–3266.
- [224] Z. Chen, A. Lohr, C. R. Saha-Möller, F. Würthner, *Chem. Soc. Rev.* **2009**, *38*, 564–584.
- [225] R. Bonnett, *Chem. Soc. Rev.* **1995**, *24*, 19.
- [226] A. E. O'Connor, W. M. Gallagher, A. T. Byrne, *Photochem. Photobiol.* **2009**, *85*, 1053–1074.
- [227] M. Ethirajan, Y. Chen, P. Joshi, R. K. Pandey, *Chem. Soc. Rev.* **2011**, *40*, 340–362.
- [228] K. Bartkowski, M. Dimitrova, P. J. Chmielewski, D. Sundholm, M. Pawlicki, *Chem. Eur. J.* **2019**, *25*, 15477–15482.
- [229] K. Bartkowski, M. Pawlicki, *Angew. Chem. Int. Ed.* **2021**, *60*, 9063–9070.
- [230] K. N. Panda, R. Sengupta, A. Kumar, M. Ravikanth, *J. Org. Chem.* **2021**, *86*, 3778–3784.
- [231] A. Sharma, M. Ravikanth, *Dalton Trans.* **2025**, *54*, 6935–6945.
- [232] Y. Hirai, Y. Kawazoe, K. Yamashita, *Chem. Eur. J.* **2024**, *30*, e202403097.
- [233] T. Ito, Y. Hayashi, S. Shimizu, J.-Y. Shin, N. Kobayashi, H. Shinokubo, *Angew. Chem. Int. Ed.* **2012**, *51*, 8542–8545.
- [234] R. Nozawa, H. Tanaka, W.-Y. Cha, Y. Hong, I. Hisaki, S. Shimizu, J.-Y. Shin, T. Kowalczyk, S. Irle, D. Kim, H. Shinokubo, *Nat. Commun.* **2016**, *7*, 13620.
- [235] M. Yamashina, Y. Tanaka, R. Lavendomme, T. K. Ronson, M. Pittelkow, J. R. Nitschke, *Nature* **2019**, *574*, 511–515.
- [236] Y. Takiya, T. Saito, N. Toriumi, M. Uchiyama, *Nat. Commun.* **2025**, *16*, 3067.
- [237] K. Ueta, J. Kim, S. Ooi, J. Oh, J. Shin, A. Nakai, M. Lim, T. Tanaka, D. Kim, A. Osuka, *J. Am. Chem. Soc.* **2021**, *143*, 7958–7967.
- [238] F. Wu, J. Xu, H. Gao, C. Li, S. Xu, H. Uno, Y. Xu, Y. Zhao, Z. Shen, *Chem. Commun. (Camb.)* **2021**, *57*, 383–386.
- [239] K. Ueta, A. Nakai, T. Tanaka, A. Osuka, *Chem. Asian J.* **2021**, *16*, 2253–2256.
- [240] Y. Yamamoto, A. Yamamoto, S.-Y. Furuta, M. Horie, M. Kodama, W. Sato, K.-Y. Akiba, S. Tsuzuki, T. Uchimar, D. Hashizume, F. Iwasaki, *J. Am. Chem. Soc.* **2005**, *127*, 14540–14541.
- [241] J. A. Cissell, T. P. Vaid, G. P. A. Yap, *Org. Lett.* **2006**, *8*, 2401–2404.
- [242] N. Halder, M. Sangeetha, D. Usharani, H. Rath, *J. Org. Chem.* **2020**, *85*, 2059–2067.
- [243] T. Satoh, M. Minoura, H. Nakano, K. Furukawa, Y. Matano, *Angew. Chem. Int. Ed.* **2016**, *55*, 2235–2238.
- [244] A. Nishiyama, M. Fukuda, S. Mori, K. Furukawa, H. Fliegl, H. Furuta, S. Shimizu, *Angew.*

Chem. Int. Ed. **2018**, *57*, 9728–9733.

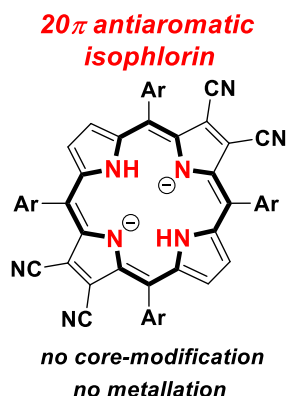
- [245] H. Kamiya, T. Kondo, T. Sakida, S. Yamaguchi, H. Shinokubo, *Chem. Eur. J.* **2012**, *18*, 16129–16135.
- [246] K. Sudoh, K. Furukawa, H. Nakano, S. Shimizu, Y. Matano, *Heteroat. Chem.* **2018**, *29*, e21456.
- [247] E. Vogel, M. Sicken, P. Röhrig, H. Schmickler, J. Lex, O. Ermer, *Angew. Chem., Int. Ed. Engl.* **1988**, *27*, 411–414.
- [248] J. Yan, M. Takakusaki, Y. Yang, S. Mori, B. Zhang, Y. Feng, M. Ishida, H. Furuta, *Chem. Commun. (Camb.)* **2014**, *50*, 14593–14596.
- [249] E. Nojman, A. Berlicka, L. Szterenberga, L. Latos-Grażyński, *Inorg. Chem.* **2012**, *51*, 3247–3260.
- [250] R. Grigg, *J. Chem. Soc. C* **1971**, 3664–3668.
- [251] B. Adinarayana, M. Das, C. H. Suresh, A. Srinivasan, *Chem. Eur. J.* **2019**, *25*, 4683–4687.
- [252] M. Umetani, T. Tanaka, T. Kim, D. Kim, A. Osuka, *Angew. Chem. Int. Ed.* **2016**, *55*, 8095–8099.
- [253] J. L. Sessler, S. J. Weghorn, Y. Hiseada, V. Lynch, *Chem. Eur. J.* **1995**, *1*, 56–67.
- [254] D. Xie, Y. Liu, Y. Rao, G. Kim, M. Zhou, D. Yu, L. Xu, B. Yin, S. Liu, T. Tanaka, N. Aratani, A. Osuka, Q. Liu, D. Kim, J. Song, *J. Am. Chem. Soc.* **2018**, *140*, 16553–16559.
- [255] S. P. Panchal, V. G. Anand, *Org. Lett.* **2017**, *19*, 4854–4857.
- [256] E. Pacholska-Dudziak, F. Ulatowski, Z. Ciunik, L. Latos-Grażyński, *Chem. Eur. J.* **2009**, *15*, 10924–10929.
- [257] H. J. Callot, T. Tschamber, E. Schaeffer, *Tetrahedron Lett.* **1975**, *16*, 2919–2922.
- [258] E. Ganapathi, W.-Z. Lee, M. Ravikanth, *J. Org. Chem.* **2014**, *79*, 9603–9612.
- [259] K. S. Anju, M. Das, B. Adinarayana, C. H. Suresh, A. Srinivasan, *Angew. Chem. Weinheim Bergstr. Ger.* **2017**, *129*, 15873–15877.
- [260] N. Grover, G. Emandi, B. Twamley, B. Khurana, V. Sol, M. O. Senge, *Eur. J. Org. Chem.* **2020**, 6489–6496.
- [261] R. Sengupta, M. Ravikanth, *Tetrahedron* **2021**, *88*, 132126.
- [262] F. Szydlo, B. Andrioletti, E. Rose, *Org. Lett.* **2006**, *8*, 2345–2348.
- [263] L. Swoboda, J. Klopff, M. Fest, A. Friedrich, M. Buckel, I. Krummenacher, H. Braunschweig, B. Engels, H. Helten, *J. Am. Chem. Soc.* **2026**, *148*, 2639–2651.
- [264] S. Shimizu, W.-S. Cho, J. L. Sessler, H. Shinokubo, A. Osuka, *Chem. Eur. J.* **2008**, *14*, 2668–2678.
- [265] T. Y. Gopalakrishna, J. S. Reddy, V. G. Anand, *Angew. Chem. Int. Ed.* **2014**, *53*, 10984–10987.
- [266] H. S. Udaya, V. G. Anand, *Org. Lett.* **2025**, *27*, 9964–9969.
- [267] S. Shimizu, V. G. Anand, R. Taniguchi, K. Furukawa, T. Kato, T. Yokoyama, A. Osuka, *J. Am. Chem. Soc.* **2004**, *126*, 12280–12281.

- [268] Y. Tanaka, S. Saito, S. Mori, N. Aratani, H. Shinokubo, N. Shibata, Y. Higuchi, Z. S. Yoon, K. S. Kim, S. B. Noh, J. K. Park, D. Kim, A. Osuka, *Angew. Chem. Int. Ed.* **2008**, *47*, 681–684.
- [269] M. G. P. M. Neves, R. M. Martins, A. C. Tomé, A. J. D. Silvestre, A. M. S. Silva, V. Félix, J. A. S. Cavaleiro, M. G. B. Drew, *Chem. Commun.* **1999**, 385–386.
- [270] J. Sankar, S. Mori, S. Saito, H. Rath, M. Suzuki, Y. Inokuma, H. Shinokubo, K. S. Kim, Z. S. Yoon, J.-Y. Shin, J. M. Lim, Y. Matsuzaki, O. Matsushita, A. Muranaka, N. Kobayashi, D. Kim, A. Osuka, *J. Am. Chem. Soc.* **2008**, *130*, 13568–13579.
- [271] S. Mori, A. Osuka, *J. Am. Chem. Soc.* **2005**, *127*, 8030–8031.
- [272] T. Higashino, A. Osuka, *Chem. Asian J.* **2013**, *8*, 1994–2002.
- [273] S.-I. Ishida, T. Higashino, S. Mori, H. Mori, N. Aratani, T. Tanaka, J. M. Lim, D. Kim, A. Osuka, *Angew. Chem. Int. Ed.* **2014**, *53*, 3427–3431.
- [274] T. Higashino, J. M. Lim, T. Miura, S. Saito, J.-Y. Shin, D. Kim, A. Osuka, *Angew. Chem. Int. Ed Engl.* **2010**, *49*, 4950–4954.
- [275] J. L. Sessler, D. Seidel, V. Lynch, *J. Am. Chem. Soc.* **1999**, *121*, 11257–11258.
- [276] Y. Liu, L. Xu, X. Jin, B. Yin, Y. Rao, M. Zhou, J. Song, A. Osuka, *Chem. Sci.* **2024**, *15*, 11402–11407.
- [277] S. Saito, A. Osuka, *Chem. Eur. J.* **2006**, *12*, 9095–9102.
- [278] S. Saito, K. S. Kim, Z. S. Yoon, D. Kim, A. Osuka, *Angew. Chem. Int. Ed.* **2007**, *46*, 5591–5593.
- [279] S. Saito, J.-Y. Shin, J. M. Lim, K. S. Kim, D. Kim, A. Osuka, *Angew. Chem. Int. Ed.* **2008**, *47*, 9657–9660.
- [280] M.-C. Yoon, J.-Y. Shin, J. M. Lim, S. Saito, T. Yoneda, A. Osuka, D. Kim, *Chem. Eur. J.* **2011**, *17*, 6707–6715.
- [281] G. Karthik, A. Srinivasan, C. H. Suresh, T. K. Chandrashekar, *Chem. Commun.* **2014**, *50*, 12127–12130.
- [282] H. Kido, J.-Y. Shin, H. Shinokubo, *Angew. Chem. Int. Ed.* **2013**, *52*, 13727–13730.
- [283] S. Shimizu, N. Aratani, A. Osuka, *Chem. Eur. J.* **2006**, *12*, 4909–4918.
- [284] E. Vogel, M. Michels, L. Zander, J. Lex, N. S. Tuzun, K. N. Houk, *Angew. Chem. Int. Ed.* **2003**, *42*, 2857–2862.
- [285] G. Hohlneicher, D. Bremm, J. Wytke, J. Bley-Esrich, J.-P. Gisselbrecht, M. Gross, M. Michels, J. Lex, E. Vogel, *Chem. Eur. J.* **2003**, *9*, 5636–5642.
- [286] Y. Tanaka, H. Mori, T. Koide, H. Yorimitsu, N. Aratani, A. Osuka, *Angew. Chem. Int. Ed.* **2011**, *50*, 11460–11464.
- [287] W.-Y. Cha, T. Soya, T. Tanaka, H. Mori, Y. Hong, S. Lee, K. H. Park, A. Osuka, D. Kim, *Chem. Commun.* **2016**, *52*, 6076–6078.
- [288] J. S. Reddy, S. Mandal, V. G. Anand, *Org. Lett.* **2006**, *8*, 5541–5543.
- [289] J. Setsune, S. Maeda, *J. Am. Chem. Soc.* **2000**, *122*, 12405–12406.

- [290] J. Setsune, Y. Katakami, N. Iizuna, *J. Am. Chem. Soc.* **1999**, *121*, 8957–8958.
- [291] N. Shivran, S. C. Gadekar, V. G. Anand, *Chem. Asian J.* **2017**, *12*, 6–20.
- [292] R. B. Woodward, *Angew. Chem.* **1960**, *72*, 651–662.
- [293] B. K. Reddy, A. Basavarajappa, M. D. Ambhore, V. G. Anand, *Chem. Rev.* **2017**, *117*, 3420–3443.
- [294] P. Pushpanandan, M. Ravikanth, *Chem. Rec.* **2022**, *22*, e202200144.
- [295] R. Cosmo, C. Kautz, K. Meerholz, J. Heinze, K. Müllen, *Angew. Chem., Int. Ed. Engl.* **1989**, *28*, 604–607.
- [296] C. Liu, D.-M. Shen, Q.-Y. Chen, *J. Am. Chem. Soc.* **2007**, *129*, 5814–5815.
- [297] Q.-Y. Chen, X.-G. Chen, C. Liu, D.-M. Shen, *Synthesis (Mass.)* **2009**, *2009*, 3860–3868.
- [298] W. Suzuki, H. Kotani, T. Ishizuka, Y. Shiota, K. Yoshizawa, T. Kojima, *Angew. Chem. Int. Ed.* **2018**, *57*, 1973–1977.
- [299] W. Suzuki, H. Kotani, T. Ishizuka, T. Kojima, *J. Am. Chem. Soc.* **2019**, *141*, 5987–5994.
- [300] A. Weiss, M. C. Hodgson, P. D. W. Boyd, W. Siebert, P. J. Brothers, *Chem. Eur. J.* **2007**, *13*, 5982–5993.
- [301] P. J. Brothers, *Inorg. Chem.* **2011**, *50*, 12374–12386.
- [302] T. P. Vaid, *J. Am. Chem. Soc.* **2011**, *133*, 15838–15841.
- [303] J. Conradie, P. J. Brothers, A. Ghosh, *Inorg. Chem.* **2019**, *58*, 4634–4640.
- [304] J. A. Cissell, T. P. Vaid, A. L. Rheingold, *J. Am. Chem. Soc.* **2005**, *127*, 12212–12213.
- [305] J. A. Cissell, T. P. Vaid, G. P. A. Yap, *J. Am. Chem. Soc.* **2007**, *129*, 7841–7847.
- [306] H.-E. Song, J. A. Cissell, T. P. Vaid, D. Holten, *J. Phys. Chem. B* **2007**, *111*, 2138–2142.
- [307] M. Kon-no, J. Mack, N. Kobayashi, M. Suenaga, K. Yoza, T. Shinmyozu, *Chem. Eur. J.* **2012**, *18*, 13361–13371.
- [308] T. Nakabuchi, M. Nakashima, S. Fujishige, H. Nakano, Y. Matano, H. Imahori, *J. Org. Chem.* **2010**, *75*, 375–389.
- [309] X. Zhan, Y. Jin, D. Qi, T. Sun, J. Jiang, *Chem. Eur. J.* **2022**, *28*, e202201125.
- [310] K. Yamashita, K. Nakajima, Y. Honda, T. Ogawa, *Chem. Eur. J.* **2020**, *26*, 3633–3640.

Chapter 2.

Synthesis of Antiaromatic Isophlorins without Metalation or Core-Modification



Abstract: Isophlorins (two-electron-reduced porphyrins) with 20π antiaromaticity have been synthesized by metalation or core modification (replacing the inner NHs with less bulky atoms) thus far. The core-modification number (CMN) is an important factor for the stability of isophlorins against their oxidation to porphyrins. However, isophlorins with small CMN (≤ 2), i.e., without significant core modification, are difficult to synthesize and important for understanding their structure–antiaromaticity relationships. Herein, the synthesis of free-base (metal-free) antiaromatic isophlorins with no core modification (CMN = 0) is reported for the first time in the literature. β -Tetracyanoporphyrins were successfully reduced by hydrazine to their corresponding isophlorins under aerobic conditions. These porphyrin/isophlorin transformations are reversible. Their structure and antiaromaticity were studied via ^1H NMR and UV-vis/near-infrared absorption spectroscopy, X-ray diffraction and theoretical calculations.

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2.1 Introduction

Isophlorins are two-electron-reduced species of porphyrins and were first proposed by Woodward in 1960 as intermediates in the synthesis of porphyrins (Figure 2.1a).^[1–3] Isophlorins have 20π cyclic-conjugated electrons and, therefore, potentially have an antiaromatic character. They are generally unstable and difficult to isolate because of their antiaromaticity and high sensitivity to oxidation. Isophlorin has four hydrogen atoms on each inner nitrogen atom of the macrocycle. Because of the steric hindrance of the hydrogen atoms, isophlorin exhibits the derivation from their planarity which causes the decrease of their antiaromaticity. Their further deformation by the *N*-alkylation affords stable isophlorin without antiaromatic character (Figure 2.1b).^[4–7]

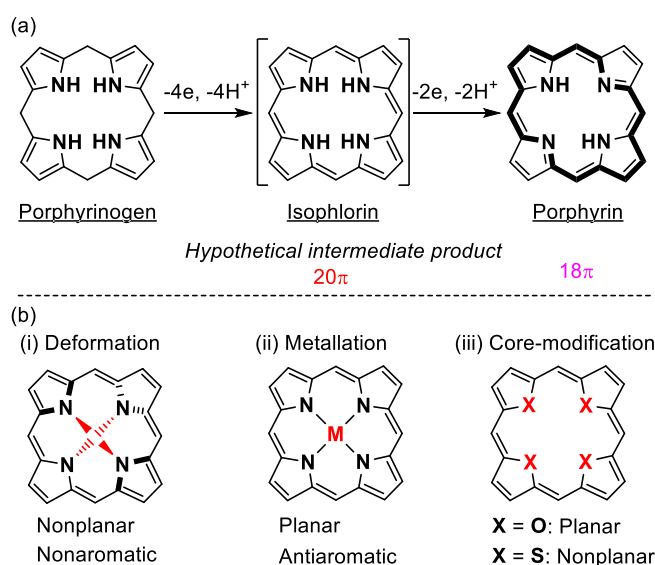
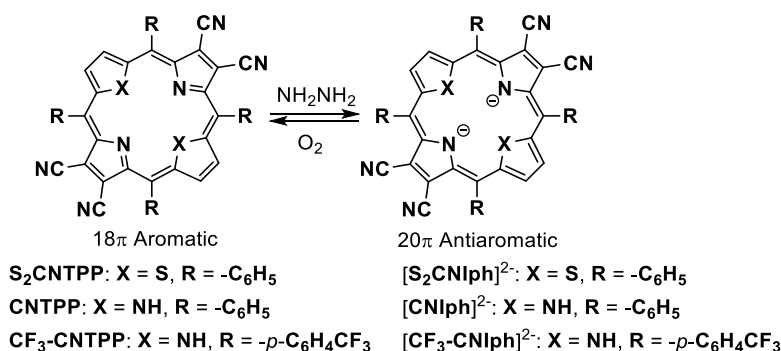


Figure 2.1 (a) Proposed scheme for porphyrin formation by oxidation of porphyrinogen via the hypothetical intermediate isophlorin.^[1–3] (b) Characterized and/or isolated isophlorins in the literature.^[3,8–16]

Planar and hence antiaromatic isophlorins have been synthesized by two approaches (Figure 1b). One approach is metallation. The two-electron reduction of Zn-tetraarylporphyrin produced an isophlorin with antiaromatic character, as revealed by ^1H NMR studies.^[8] In addition, tetravalent elements such as Si^{IV} ^[10] or Ge^{IV} ^[11] or their analogs such as $\text{C}=\text{C}$ ^[14] or $\text{B}-\text{B}$ ^[12] have been used to obtain antiaromatic isophlorins. These isophlorins were highly air-sensitive and should be handled under an inert atmosphere. Another approach is core modification, which involves replacing the inner NHs with less bulky O or S atoms.^[9,13,15,16] In particular, isophlorin derivatives with electron-withdrawing substituents, such as $-\text{C}_6\text{F}_5$, were stable even under atmospheric conditions and exhibited strong antiaromaticity.^[13,15,16] The core-modification approach inhibits π -conjugation of the heteroatoms and destabilizes the oxidized 18π aromatic system, thereby stabilizing the isophlorin. Therefore, the core-modification number (CMN) is an important factor for the stability of isophlorins. Synthesizing an

isophlorin with a CMN of two or less is difficult; however, it is important for understanding the structure–antiaromaticity relationships of isophlorins.

Yamashita et al. have reported the synthesis and antiaromaticity of β -tetracyano-21,23-dithiaisophlorin S_2CNlph (CMN = 2) (Scheme 2.1).^[17] Weak reducing agents such as hydrazine were used to reduce the corresponding dithiaporphyrin S_2CNTPP to its isophlorin S_2CNlph , which was stable in the presence of the reducing agent even under atmospheric conditions. Moreover, the reduction of S_2CNTPP to S_2CNlph was reversible. Using cyano groups as peripheral substituents increased the reduction potential of the porphyrin core and stabilized the antiaromatic isophlorin by π -conjugation. Based on this concept, in this study, the author synthesized β -tetracyanoisophlorins $CNlph$ and CF_3 - $CNlph$ (CMN = 0) via the reduction of β -tetracyanoporphyrins $CNTPP$ and CF_3 - $CNTPP$, respectively, and studied their antiaromatic character. Although the synthesis, structure, and strong electron-accepting nature of β -tetracyanoporphyrins have been widely explored^[18–28] since the first report in 1973,^[29] their two-electron-reduced products, i.e. isophlorins, have not been isolated and explored, except for their UV-vis absorption studies during in situ electrolysis.^[20] In this study, isophlorins have been isolated by chemical reduction under ambient conditions. To the best of the author's knowledge, $CNlph$ and CF_3 - $CNlph$ are the first free-base isophlorins with a 20π antiaromatic character reported in the literature.



Scheme 2.1 Redox transformations between 18π aromatic β -tetracyanoporphyrins and the corresponding 20π antiaromatic isophlorins.

2.2 Results and Discussion

2.2.1 Synthesis of Isophlorin Precursors

β -Tetracyanotetraarylporphyrins $CNTPP$ and CF_3 - $CNTPP$ were synthesized using a modified synthesis of the dithia analog S_2CNTPP from the literature.^[17] Similar to those of S_2CNTPP , the properties of $CNTPP$ and CF_3 - $CNTPP$ exhibited strong solvent dependence. The NMR and UV-vis absorption spectra of $CNTPP$ and CF_3 - $CNTPP$ in nonpolar solvents confirmed its 18π aromatic nature. In contrast, the NMR and UV-vis spectra recorded in dimethyl sulfoxide (DMSO) strongly

suggested that CNTPPs was spontaneously reduced by one electron to generate its anion radical. The ^1H NMR and UV-vis spectra of CNTPP in DMSO exhibited broader peaks than those in nonpolar solvents.

The redox potentials of CNTPP, $\text{CF}_3\text{-CNTPP}$ and S_2CNTPP determined by cyclic and differential pulse voltammetry are shown in Figure 2.2 and Table 2.1. Both CNTPP and $\text{CF}_3\text{-CNTPP}$ exhibit two reversible reduction waves. In the nonpolar solvent CH_2Cl_2 , the reduction potentials of CNTPP (-0.75 and -1.05 V) were ~ 0.2 V more negative than those of S_2CNTPP (-0.54 and -0.81 V). Those of $\text{CF}_3\text{-CNTPP}$ (-0.60 and -0.94 V) were more positive than those of CNTPP because of the effect of the electron-withdrawing trifluoromethyl substituents on $\text{CF}_3\text{-CNTPP}$. In DMSO, the redox potentials of $\text{CF}_3\text{-CNTPP}$ were positively shifted (-0.47 and -0.74 V), indicating that the reduced states were more stable in DMSO. Similar solvent dependence was also reported by us for the dithia analog S_2CNTPP .^[17]

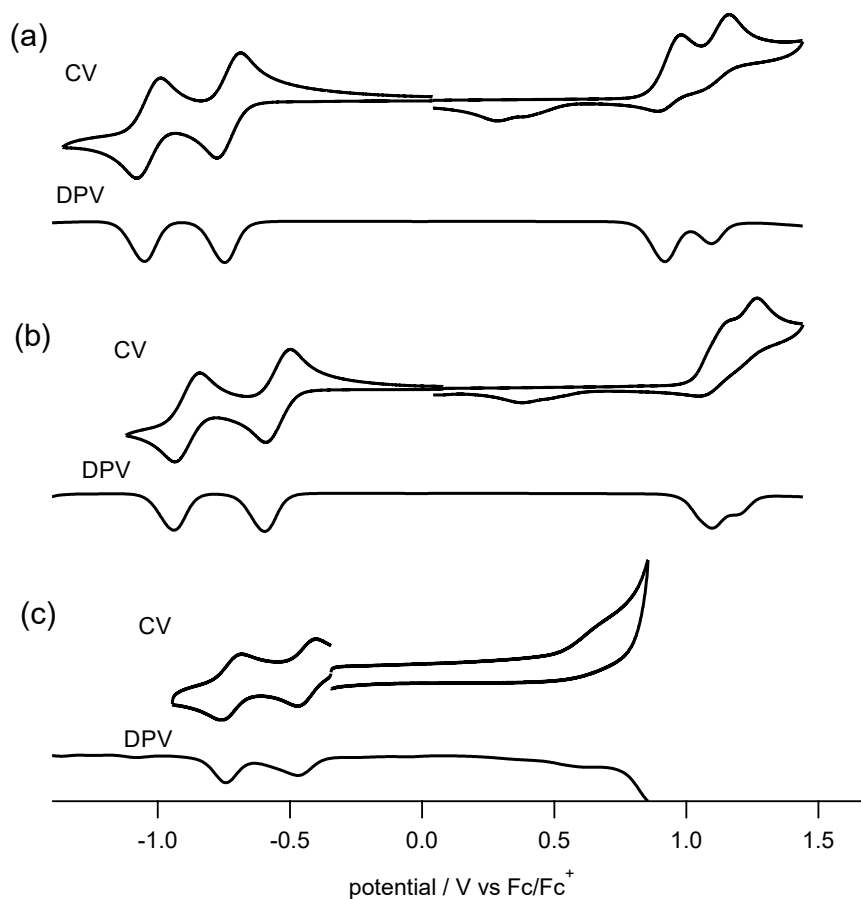


Figure 2.2 Cyclic and differential pulse voltammogram of (a) CNTPP in CH_2Cl_2 , (b) $\text{CF}_3\text{-CNTPP}$ in CH_2Cl_2 and (c) $\text{CF}_3\text{-CNTPP}$ in DMSO.

Table 2.1 Half-wave potentials (V vs Fc/Fc⁺) of CNTPP, CF₃-CNTPP and S₂CNTPP. Potential values were obtained from differential pulse voltammetry (DPV).

	solvent	E_{ox1}	E_{red1}	E_{red2}
CNTPP	CH ₂ Cl ₂	0.92	−0.75	−1.05
CF ₃ -CNTPP	CH ₂ Cl ₂	1.10	−0.60	−0.94
	DMSO	− [b]	−0.47	−0.74
S ₂ CNTPP [a]	CH ₂ Cl ₂	1.08	−0.54	−0.81
	DMSO	− [b]	−0.33	−0.61

[a] Data from ref 17. [b] Out of the potential window.

2.2.2 ¹H NMR Study in the Reduction to Synthesis Isophlorins

Similar to the reduction of S₂CNTPP, the reduction of CNTPP and CF₃-CNTPP was performed to obtain the isophlorins [CNIph]^{2−} and [CF₃-CNIph]^{2−}. The treatment of CNTPP and CF₃-CNTPP with hydrazine monohydrate in DMSO resulted in a rapid color change from brown to reddish-purple, suggesting the formation of the corresponding isophlorin (Figure 2.3). However, the ¹H NMR spectrum of the reduced product of CNTPP and NH₂NH₂·H₂O in [D₆]DMSO was unclear (Figure 2.4b). In contrast, the ¹H NMR spectrum of the reduced product of CF₃-CNTPP (Figure 2.5) indicated that the antiaromatic isophlorin dianion[CF₃-CNIph]^{2−} was the sole product. The conversion of aromatic compounds to antiaromatic compounds is known to cause the high field shift characteristic of protons (Chapter 1.2.2.3). A sharp signal for β protons was observed at 4.99 ppm, which was considerably upfield compared to that of CF₃-CNTPP and comparable to that of [S₂CNIph]^{2−}. Moreover, this signal was observed as a doublet with a small *J* value (1.7 Hz) owing to long-range coupling with the NH protons (Figure 2.6). A broad NH signal was observed at 16 ppm, and the integral ratio between the NH and β proton signals was 1:2. These results indicate that two NH protons were present in the product and were located on the nitrogen atoms of the unsubstituted pyrrole rings.

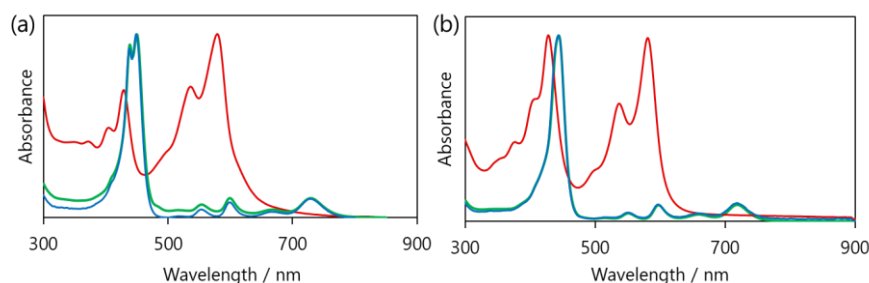


Figure 2.3 UV/vis/NIR absorption spectra of (a) [CNIph]^{2−}/ CNTPP and (b) [CF₃-CNIph]^{2−}/ CF₃-CNTPP. Blue: in CH₂Cl₂ (i.e. CNTPP or CF₃-CNTPP), red: in DMSO in the presence of 1% NH₂NH₂·H₂O (i.e. [CNIph]^{2−} or [CF₃-CNIph]^{2−}), green: the extracted product (in CH₂Cl₂) by CHCl₃ from the DMSO/water solution of [CNIph]^{2−} or [CF₃-CNIph]^{2−}.

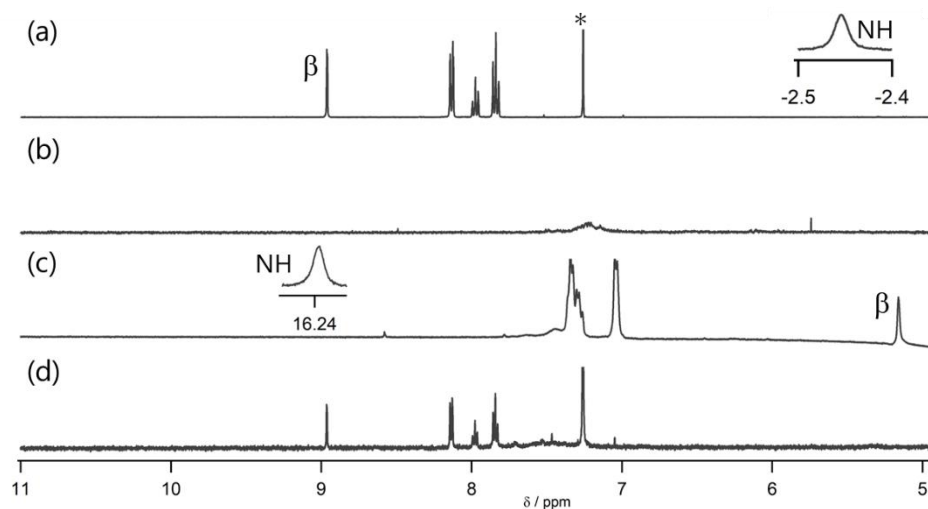


Figure 2.4 ^1H NMR spectra showing the reduction of CNTPP to $[\text{CNIph}]^{2-}$. (a) CNTPP in CDCl_3 . (b) The resultant solution of CNTPP in $[\text{D}_6]\text{DMSO}$ by the addition of 1 drop of $\text{NH}_2\text{NH}_2 \cdot \text{H}_2\text{O}$. (c) $[\text{CNIph}]^{2-}$ generated by the in-situ reduction of CNTPP in neat $\text{ND}_2\text{ND}_2 \cdot \text{D}_2\text{O}$. Inset shows the NH signals in neat $\text{NH}_2\text{NH}_2 \cdot \text{H}_2\text{O}$. (d) The extracted product (in CDCl_3) by CHCl_3 from the DMSO/water solution of $[\text{CNIph}]^{2-}$.

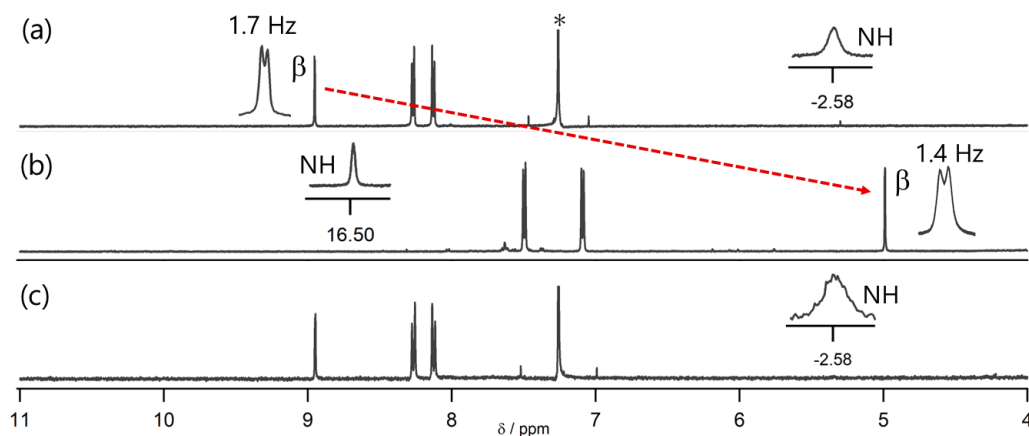


Figure 2.5 ^1H NMR (500 MHz) spectra of (a) $\text{CF}_3\text{-CNTPP}$ in CDCl_3 , (b) $[\text{CF}_3\text{-CNIph}]^{2-}$ generated by in situ reduction using $\text{NH}_2\text{NH}_2 \cdot \text{H}_2\text{O}$ in $[\text{D}_6]\text{DMSO}$, and (c) the extracted product by CHCl_3 from the solution of $[\text{CF}_3\text{-CNIph}]^{2-}$ in DMSO/water in CDCl_3 .

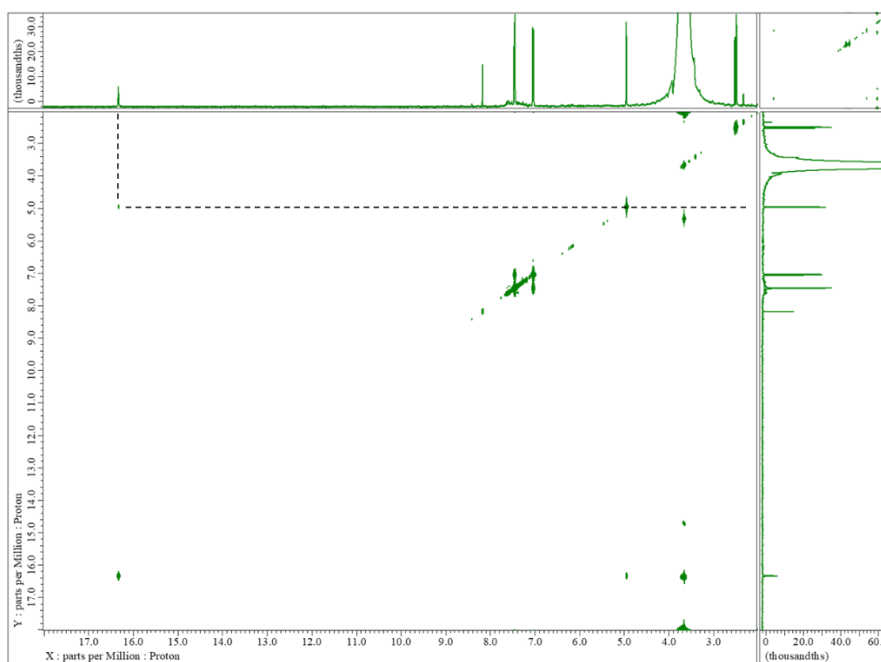


Figure 2.6 ^1H COSY NMR (500 MHz, $[\text{D}_6]\text{DMSO} + \text{NH}_2\text{NH}_2 \cdot \text{H}_2\text{O}$) spectrum of $[\text{CF}_3\text{-CNIph}]^{2-}$.

The unclear ^1H NMR spectrum of the reduced product of CNTPP may be owing to the incomplete formation of $[\text{CNIph}]^{2-}$, and the 19π radical may exist in the solution as an equilibrium mixture. Nonetheless, the formation of $[\text{CNIph}]^{2-}$ was accomplished using neat $\text{NH}_2\text{NH}_2 \cdot \text{H}_2\text{O}$ or $\text{ND}_2\text{ND}_2 \cdot \text{D}_2\text{O}$ as solvents, as confirmed by ^1H NMR analysis (Figure 2.4c).

In neither isophlorins ($[\text{CNIph}]^{2-}$ and $[\text{CF}_3\text{-CNIph}]^{2-}$) nor porphyrins (CNTPP and $\text{CF}_3\text{-CNTPP}$), the corresponding proton tautomers were not observed by ^1H NMR. The energy difference between tautomers of a tetracyanoporphyrin has been estimated to be 8.75 kcal/mol based on quantum chemical calculations. The energy difference (ΔG) between the tautomers of the isophlorin and the porphyrin was estimated from DFT calculations (B3LYP/6-31+G(d,p)). For simplicity, only $[\text{CNIph}]^{2-}$ and CNTPP were calculated, and found it to be 12.06 and 6.53 kcal/mol, respectively. These values were consistent with ^1H NMR analyses and X-ray diffraction analyses (described below).^[30]

2.2.3 UV-vis/NIR Absorption Spectra of Porphyrins and Isophlorins

The UV-vis/near-infrared (NIR) spectra of $[\text{CF}_3\text{-CNIph}]^{2-}$ in $\text{DMSO}/\text{NH}_2\text{NH}_2 \cdot \text{H}_2\text{O}$ (Figure 2.7) were similar to those of the previously reported dithia analog $[\text{S}_2\text{CNIph}]^{2-}$, with two absorption bands around 420 and 580 nm and a weak and broad absorption band in the 700–1100 nm region. Time-dependent density functional theory (TDDFT) calculations suggested that these absorption bands could be assigned to $S_0 \rightarrow S_1$ (HOMO $\rightarrow$ LUMO), $S_0 \rightarrow S_2$ (HOMO $\rightarrow$ LUMO+1), and $S_0 \rightarrow S_3$ (HOMO-1 $\rightarrow$ LUMO) (Figure 2.8, Table E2.2). Notably, the reduced product of CNTPP also afforded a similar spectrum to that of $[\text{CNIph}]^{2-}$ under the same conditions (Figure 2.3a) despite the incomplete

formation of $[\text{CNlph}]^{2-}$ as suggested by ^1H NMR analysis (Figure 2.4b). These results indicate that the redox interconversion is preferential towards the formation of the target product $[\text{CNlph}]^{2-}$; however, the equilibrium of $[\text{CNlph}]^{2-}$ with a small amount of incompletely reduced radical species causes significant broadening of signals in the ^1H NMR spectrum.

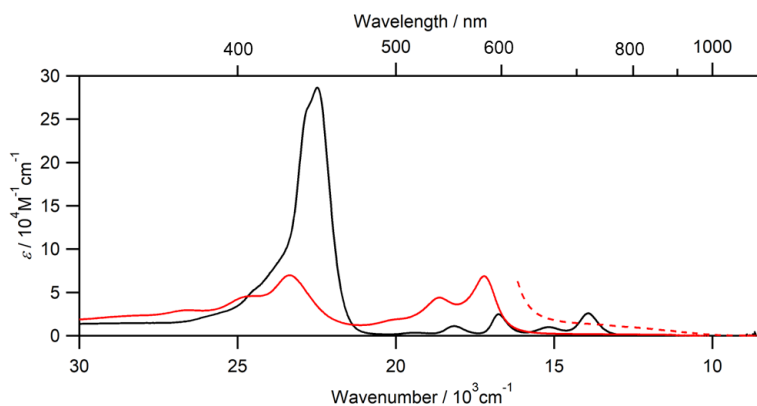


Figure 2.7 UV-vis/NIR absorption spectra of $\text{CF}_3\text{-CNTTP}$ in CH_2Cl_2 (black) and $[\text{CF}_3\text{-CNlph}]^{2-}$ in DMSO in the presence of $\text{NH}_2\text{NH}_2\cdot\text{H}_2\text{O}$ (1%) (red). The dashed line was magnified 10 times.

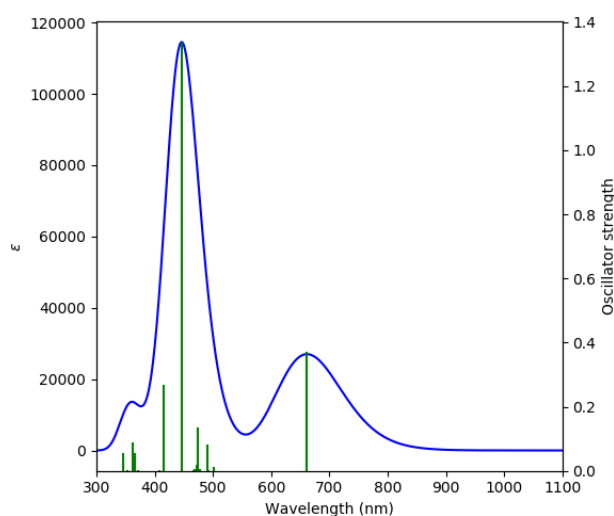


Figure 2.8 Calculated (TDDFT) UV-vis/NIR absorption spectrum of $[\text{CNlph}]^{2-}$. (vacuum)

2.2.4 Stability of Isophlorins

The obtained isophlorin $[\text{CF}_3\text{-CNlph}]^{2-}$ was stable in the presence of hydrazine even under the air. ^1H NMR measurements of the solution of $[\text{CF}_3\text{-CNlph}]^{2-}$ left to stand for more than a week did not observe peaks for any degraded products. Changes in absorption spectra of $[\text{CF}_3\text{-CNlph}]^{2-}$ were dependent on hydrazine concentration; a 10% hydrazine solution of $[\text{CF}_3\text{-CNlph}]^{2-}$ resulted in

only a 15% decrease in absorbance in one day.

Similar to the oxidation of $[\text{S}_2\text{CNiPh}]^{2-}$ to S_2CNTPP , $[\text{CNiPh}]^{2-}$ and $[\text{CF}_3\text{-CNiPh}]^{2-}$ can undergo oxidation and transform into porphyrins CNTPP and $\text{CF}_3\text{-CNTPP}$, respectively. During the attempted extraction of $[\text{CF}_3\text{-CNiPh}]^{2-}$ in a DMSO/water solution by CHCl_3 , $[\text{CF}_3\text{-CNiPh}]^{2-}$ underwent oxidation by air to afford CNTPP and $\text{CF}_3\text{-CNTPP}$. The concentration of the CHCl_3 solution and the analysis of the resulting solid using ^1H NMR (Figures 2.4 and 2.5) and UV-Vis/NIR (Figure 2.3) confirmed that the extract contained porphyrins CNTPP and $\text{CF}_3\text{-CNTPP}$.

2.2.5 Single Crystal Structures of Isophlorins

Single crystals of the tetraphenylphosphonium (PPh_4^+) salts of isophlorins $[\text{CNiPh}]^{2-}$ and $[\text{CF}_3\text{-CNiPh}]^{2-}$ were obtained by crystallization in a methanol solution of PPh_4Br . X-ray diffraction measurements revealed the molecular structures of $(\text{PPh}_4)_2[\text{CNiPh}]$ and $(\text{PPh}_4)_2[\text{CF}_3\text{-CNiPh}]$ (Figure 2.9). The differential Fourier ($|F_o| - |F_c|$) map indicated that the two NH protons were located on the nitrogen atoms of the unsubstituted pyrrole rings. This result was consistent with ^1H NMR analyses. Both $[\text{CNiPh}]^{2-}$ and $[\text{CF}_3\text{-CNiPh}]^{2-}$ crystals exhibited small mean plane deviation values (0.13 and 0.02, respectively) (Table 2.2 and Figure 2.10), which were smaller than those for $[\text{S}_2\text{CNiPh}]^{2-}$ (0.17), indicating that $[\text{CNiPh}]^{2-}$ and $[\text{CF}_3\text{-CNiPh}]^{2-}$ have nearly planar conformations. Selected bond lengths are shown in Figure 2.11. The harmonic oscillator model of aromaticity (HOMA)^[31,32] values of the crystal structures of $[\text{CNiPh}]^{2-}$ and $[\text{CF}_3\text{-CNiPh}]^{2-}$ (Table 2.2) were within the range of typical antiaromatic porphyrinoids. The HOMA values of $[\text{CNiPh}]^{2-}$ and $[\text{CF}_3\text{-CNiPh}]^{2-}$ for pathway A were smaller than those for pathway B, whereas the HOMA values of $[\text{S}_2\text{CNiPh}]^{2-}$ for pathways A and B were comparable.

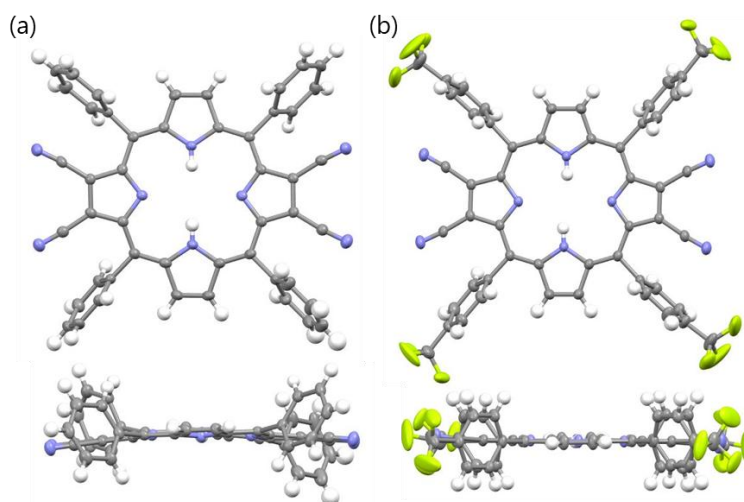


Figure 2.9 Thermal ellipsoid representations (50% probability level) of the crystal structure of (a) $(\text{PPh}_4)_2[\text{CNiPh}]$ and (b) $(\text{PPh}_4)_2[\text{CF}_3\text{-CNiPh}]$. PPh_4 cation and solvated molecules were omitted for clarity. C = gray, H = white, N = blue, and F = yellow.

Table 2.2 Mean plane deviation (mpd)^[a] and harmonic oscillator model of aromaticity (HOMA) values for the crystal structures of [CNlph](PPh₄)₂, [CF₃-CNlph](PPh₄)₂, and [S₂CNlph](PPh₄)₂^[17].

	[CNlph](PPh ₄) ₂	[CF ₃ -CNlph](PPh ₄) ₂	[S ₂ CNlph](PPh ₄) ₂
mpd (Å)	0.13	0.02	0.17
HOMA(A) ^[b]	0.325	0.535	0.501
HOMA(B) ^[c]	0.545	0.652	0.525

[a] Defined by 24 core atoms. [b] Calculated for pathway A (shown below in bold line). [c] Calculated for pathway B (shown below in bold line).

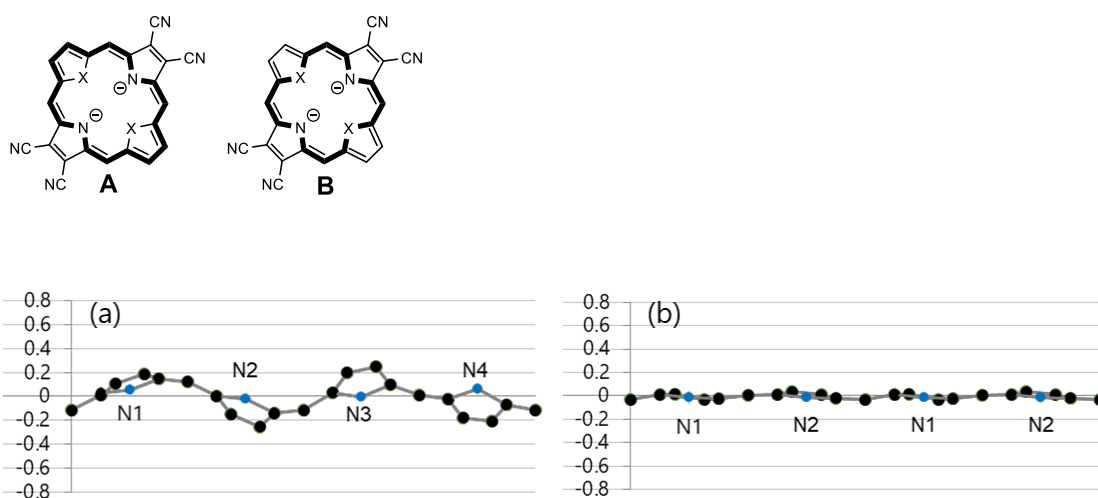


Figure 2.10 View of the skeletal deviations of the macrocycle atoms from the 24-plane for (a) [CNlph]²⁻ and (b) [CF₃-CNlph]²⁻ in the crystal.

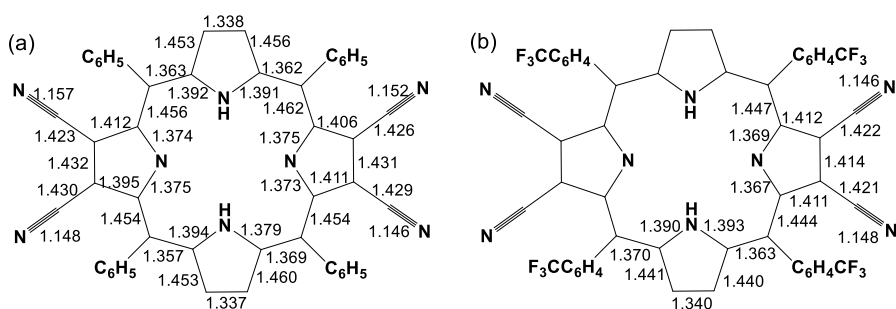


Figure 2.11 Selected bond lengths (Å) from the crystal structures of (a) (PPh₄)₂[CNlph] and (b) (PPh₄)₂[CF₃-CNlph].

The bond order of the cyano groups upon reduction of CNTPP and CF₃-CNTPP to [CNlph]²⁻ and [CF₃-CNlph]²⁻, evidenced by the crystal structure and IR spectra, was in agreement with that of a previously reported reduction of S₂CNTPP to [S₂CNlph]²⁻.^[17] The CN bond lengths of the cyano

groups in $[\text{CNIph}]^{2-}$ and $[\text{CF}_3\text{-CNIph}]^{2-}$ were longer than those in $\text{CNTPP}^{[28]}$ (Figure 2.11). The CN stretching peaks in the IR spectra of $\text{CF}_3\text{-CNTPP}$ and $[\text{CF}_3\text{-CNIph}]^{2-}$ were at 2222 and 2173 cm^{-1} , respectively, indicating a 49 cm^{-1} shift in the peak (Figure 2.12). This result is attributed to the considerable contribution of the nonaromatic quinoidal resonance structures for $[\text{CNIph}]^{2-}$ and $[\text{CF}_3\text{-CNIph}]^{2-}$.^[17]

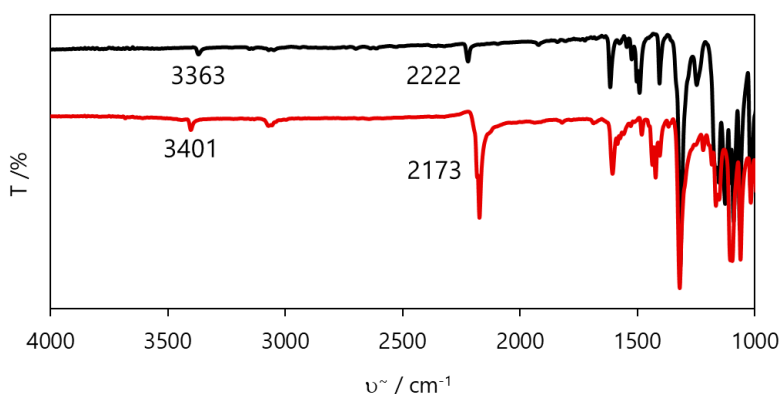


Figure 2.12 ATR-IR spectra of $\text{CF}_3\text{-CNTPP}$ (black line) and $(\text{PPh}_4)_2[\text{CF}_3\text{-CNIph}]$ (red line).

2.2.6 Quantum Chemical Calculations of Isophlorins

The anisotropy of the induced current density (AICD)^[33] and the nucleus-independent chemical shift (NICS)^[34,35] of $[\text{CNIph}]^{2-}$ also confirm its antiaromatic character. The AICD plot for $[\text{CNIph}]^{2-}$ revealed a counterclockwise ring current, as expected for antiaromatic π -systems (Figure 2.13). The contribution of the C_β -pyrrole atoms to the ring current was evidently small and that of nitrogen atoms was dominant. These results, along with the obtained HOMA values, suggest that conjugation pathway B (shown in Table 2.2) was more dominant than pathway A for both $[\text{CNIph}]^{2-}$ and $[\text{CF}_3\text{-CNIph}]^{2-}$, whereas the contributions of pathways A and B were comparable for $[\text{S}_2\text{CNIph}]^{2-}$. The NICS(0) values of $[\text{CNIph}]^{2-}$ are listed in Table 2.3, which were comparable to those of $[\text{S}_2\text{CNIph}]^{2-}$. These results suggest a similar antiaromatic character for $[\text{CNIph}]^{2-}$ and $[\text{S}_2\text{CNIph}]^{2-}$.

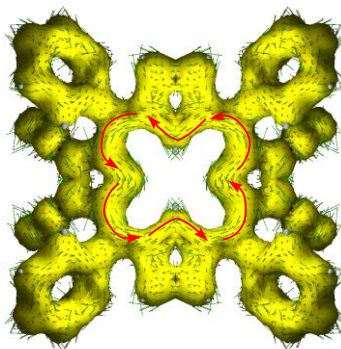
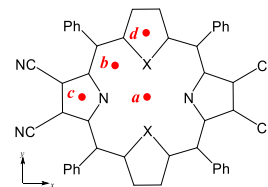


Figure 2.13 Anisotropy of the induced current density (AICD) plot for $[\text{CNIph}]^{2-}$ (isosurface value: 0.03).

Table 2.3 Nucleus-independent chemical shift (NICS(0)) HF/6-311+G**//B3LYP/6-31+G** values for [CNIph]²⁻ (X = NH) and [S₂CNIph]²⁻ (X = S).[a]

	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>
[CNIph] ²⁻	4 (23)	2 (29)	-11 (-3)	-2 (22)
[S ₂ CNIph] ²⁻	6 (30)	5 (38)	-11 (2)	-1 (28)

[a] All are NICS_{iso} values. The values in parentheses are NICS_{zz} values.



2.3 Summary

Free-base β -tetracyanoporphyrins are readily reduced by hydrazine under atmospheric conditions to afford β -tetracyanoisophlorin dianions with 20π antiaromatic character. Their structures were unambiguously confirmed by X-ray diffraction. The cyano groups as the peripheral substituents on the isophlorin macrocycle and the electron-withdrawing substituents on the phenyl rings stabilized the reduced isophlorin. These porphyrin/isophlorin transformations are reversible. To the best of the author's knowledge, these isophlorins are the first antiaromatic isophlorins prepared without metallation or core modifications. The author synthesized metal complexes of these isophlorins to further understand the relationship between their structure and properties and to elucidate the properties of the resulting isophlorins. Details are given in the next chapter.

2.4 Experimental Section

2.4.1 Instrumental and Chemicals

1,3-Dimethyl-2-imidazolidinone (DMI) was distilled using CaH₂. All other chemicals were of reagent grade and were used without any further purification unless otherwise noted. Analytical thin-layer chromatography (TLC) was performed using silica gel 60 F₂₅₄ plates. Column chromatography was performed using silica gel 60N (Kanto Chemical; spherical, neutral, 63–210 μ m). All NMR spectral data were recorded on a JEOL ECA-500 (500 MHz) or ECZ-500R (500 MHz) spectrometer at an ambient temperature (25 °C). For ¹H NMR spectra except for that in NH₂NH₂·H₂O, tetramethylsilane (δ = 0) was used as the internal standard, whereas that in NH₂NH₂·H₂O was referenced internally by tetramethylsilane (δ = 0) in CDCl₃ isolated by coaxial insert tube. For ¹³C NMR spectra except for that in NH₂NH₂·H₂O, CDCl₃ and [D₆]DMSO (δ = 77.0 and 39.5 ppm) were used as internal standards, whereas that in NH₂NH₂·H₂O was referenced internally by CDCl₃ (δ = 77.0 ppm) isolated by coaxial insert tube. High resolution electrospray ionization mass spectrometry (ESI HRMS) data were obtained using a Thermo Fisher Scientific Q-Exactive mass spectrometer. UV-vis/NIR spectral data were recorded on a Shimadzu UV-3150 or UV-3600 spectrometer, or HITACHI U-4100 spectrometer. IR spectral data were recorded on a JASCO FTIR

6100 spectrometer equipped with an attenuated total reflection (ATR) unit (ZnSe prism). The melting points were determined using a Yanaco MP-S3 melting point apparatus. Cyclic and differential pulse voltammetry measurements were performed using an ALS 630E electrochemical analyzer in N₂-saturated dry CH₂Cl₂ or DMSO solutions containing 0.1 M tetrabutylammonium hexafluorophosphate as a supporting electrolyte at ambient temperature (298 K). A conventional three-electrode cell was used with a glassy carbon working electrode, a platinum wire counter electrode, and a silver wire pseudo-reference electrode. Ferrocene was used as the internal standard in all the electrochemical experiments, and the reported potentials were corrected for the Fc/Fc⁺ couple.

2.4.2 Synthetic Procedures

7,8,17,18-Tetrabromo-5,10,15,20-tetrakis(4-trifluoromethylphenyl)porphyrin^[36]

To a solution of 5,10,15,20-tetrakis(4-trifluoromethylphenyl)porphyrin (596 mg, 0.672 mmol) in 1,2-dichloroethane (100 mL), *N*-bromosuccinimide (1388 mg, 5.402 mmol) was added. The resultant solution was refluxed for 15 h. After cooling to room temperature, the resultant solution was added triethylamine (2 mL), and then concentrated under the reduced pressure. Then, resultant solution was added the excess of MeOH to precipitate the product. The product was collected by the filtration to give the title compound as a purple solid (472 mg, 0.393 mmol, 58%). m.p. > 300 °C; ¹H NMR (500 MHz, CDCl₃): δ = 8.67 (s, 4H; PorH_b), 8.29 (d, ³J_{H-H} = 7.9 Hz, 8H; PhH), 8.06 (d, ³J_{H-H} = 7.9 Hz, 8H; PhH), -2.86 ppm (s, 2H; NH); ¹³C NMR (125 MHz, CDCl₃): δ = 148.0 (Cq), 143.7 (Cq), 139.9 (Cq), 135.4 (CH), 129.4 (CH), 126.0 (Cq), 124.6 (Cq), 119.2 ppm (Cq) (Two signals corresponding to -CF₃ and -CCF₃ carbons were not observed because of low peak intensity due to ¹³C-¹⁹F couplings.); HRMS(ESI): *m/z*: calcd for C₄₈H₂₁F₁₂N₄Br₄: 1200.8273 [*M*-H]⁻; found: 1200.8234.

[7,8,17,18-Tetrabromo-5,10,15,20-tetrakis(4-trifluoromethylphenyl)porphyrinato]nickel(II)

To a solution of 7,8,17,18-tetrabromo-5,10,15,20-tetrakis(4-trifluoromethylphenyl)porphyrin (1002 mg, 0.8331 mmol) in toluene (390 mL), bis(acetylacetonato)nickel(II) (2900 mg, 11.29 mmol) was added. The resultant solution was refluxed for 16 h. After cooling to room temperature, the resultant solution was passed through a pat of silica gel column chromatography and eluted with CH₂Cl₂, and then concentrated under the reduced pressure. Then, resultant solution was added the excess of MeOH to precipitate the product. The product was collected by the filtration to give the title compound as a purple solid (973 mg, 0.928 mmol, 93%). m.p. >300 °C; ¹H NMR (500 MHz, CDCl₃): δ = 8.49 (s, 4H; PorH_b), 7.98 (d, ³J_{H-H} = 8.1 Hz, 8H; PhH), 7.93 ppm (d, ³J_{H-H} = 8.1 Hz, 8H; PhH); ¹³C NMR (125 MHz, CDCl₃): δ = 144.2 (Cq), 142.3 (Cq), 137.0 (Cq), 134.0 (CH), 133.6 (CH), 131.1 (q, ²J_{C-F} = 32.4 Hz; -CCF₃), 125.1 (Cq), 124.4 (q, ³J_{C-F} = 3.6 Hz; CH), 124.3 (q, ¹J_{C-F} = 272.3 Hz; -CF₃), 117.5 ppm (Cq); HRMS(ESI): *m/z*: calcd for C₄₈H₂₀F₁₂N₄Br₄Ni: 1257.7540 [*M*]⁻; found: 1257.7548.

[7,8,17,18-Tetracyano-5,10,15,20-tetrakis(4-trifluoromethylphenyl)porphyrinato]nickel(II)

[7,8,17,18-Tetrabromo-5,10,15,20-tetrakis(4-trifluoromethylphenyl)porphyrinato]nickel(II) (900 mg, 0.715 mmol), CuCN (2563 mg, 28.6 mmol, 40 eq.) was mixed in freshly distilled 1,3-dimethyl-2-imidazolidinone (DMI, 73 mL). The resultant mixture was stirred at 150 °C for 16 h under N₂. The resultant mixture was cooled to room temperature, and then added a solution of FeCl₃·6H₂O (12.6 g) in H₂O (250 mL). The resultant mixture was stirred at 70 °C for 60 min. After cooling to room temperature, the product was extracted with CHCl₃, and then the organic layer was washed with aqueous NH₃ (×1), water (×1), NH₄Cl aq (×2) and brine (×1), and dried over Na₂SO₄. Solvent was removed under the reduced pressure. The crude product was purified by column chromatography (silica gel, CH₂Cl₂). Recrystallization from CHCl₃/MeOH gave the title compound as a purple solid (411 mg, 0.394 mmol, 55%). m.p. >300 °C; ¹H NMR (500 MHz, CDCl₃): δ = 8.72 (s, 4H; PorH_b), 8.00 ppm (m, 16H; PhH); ¹³C NMR (125 MHz, CDCl₃): δ = 145.9 (Cq), 139.6 (Cq), 138.4 (Cq), 135.7 (CH), 133.5 (CH), 133.0 (q, ²J_{C-F} = 32.4 Hz; -CCF₃), 125.2 (q, ³J_{C-F} = 3.6 Hz; CH), 123.9 (q, ¹J_{C-F} = 272.3 Hz; -CF₃), 122.1 (Cq), 120.1 (Cq), 110.9 ppm (Cq); HRMS(ESI): *m/z*: calcd for C₅₂H₂₀F₁₂N₈Ni: 1042.0978 [*M*]⁺; found: 1042.0972.

7,8,17,18-Tetracyano-5,10,15,20-tetrakis(4-trifluoromethylphenyl)porphyrin (CF₃-CNTPP)

To a solution of [7,8,17,18-tetracyano-5,10,15,20-tetrakis(4-trifluoromethylphenyl)porphyrinato]nickel(II) (410 mg, 0.394 mmol) in CF₃COOH (5.0 mL), conc. H₂SO₄ (5.0 mL) was added dropwise, and the resultant solution was stirred at room temperature for 2 hours. The resultant solution was neutralized by aq. NaOH. The product was extracted with CH₂Cl₂, and then the organic layer was washed with water and dried over Na₂SO₄. Solvent was removed under the reduced pressure. The crude product was purified by column chromatography (silica gel, CH₂Cl₂). Recrystallization from CHCl₃/hexane gave CF₃-CNTPP as a purple solid (156 mg, 0.159 mmol, 40%). m.p. >300 °C; ¹H NMR (500 MHz, CDCl₃) δ = 8.95 (d, ⁴J_{H-H} = 1.4 Hz, 4H; PorH_b), 8.27 (d, ³J_{H-H} = 8.1 Hz, 8H; PhH), 8.13 (d, ³J_{H-H} = 8.1 Hz, 8H; PhH), -2.58 ppm (brs, 2H; NH); ¹³C NMR (125 MHz, CDCl₃) δ = 148.9 (Cq), 134.5 (CH), 131.8 (CH), 125.1 (CH), 121.5 (Cq), 111.6 ppm (Cq) (Several signals were not observed because of its significantly low solubility.); IR (ATR): ν̃ = 3363, 3152, 3137, 3068, 3046, 2222, 1617, 1525, 1504, 1492, 1407, 1318, 1249, 1154, 1127, 1107, 1092, 1065, 1019, 964, 856, 834, 804, 773, 735, 700, 667 cm⁻¹; UV/Vis (CH₂Cl₂): λ_{max} (Log ε) = 445 (5.46), 516 (3.49), 551 (4.03), 597 (4.38), 660 (3.98), 718 nm (4.40); HRMS(ESI): *m/z*: calcd for C₅₂H₂₁F₁₂N₈: 985.1703 [*M-H*]⁻; found: 985.1710; elemental analysis calcd (%) for C₅₂H₂₂N₈F₁₂: C 63.29, H 2.25, N 11.36; found: C 63.17, H 2.39, N 11.35.

Reduction of CNTPP and isolation of (PPh₄)₂[CNIph]

CNTPP^[37] was dissolved in NH₂NH₂·H₂O or ND₂ND₂·D₂O. ¹H NMR and UV-vis/NIR analyses revealed the quantitative formation of [CNIph]²⁻, potentially as a hydrazinium salt. For the isolation of [CNIph]²⁻, CNTPP (19.3 mg, 27.0 μmol) was dissolved in 1.25 mL of NH₂NH₂·H₂O. A saturated solution of tetraphenylphosphonium bromide in methanol was gently poured into the resulting solution and left to stand for 5 hours. Then, the precipitated microcrystals of (PPh₄)₂[CNIph] were collected by filtration and dried under vacuum to afford (PPh₄)₂[CNIph] as brown microcrystals (18.2 mg, 13.4 μmol, 50%). M.p. (PPh₄ salt) = 141–144 °C; ¹H NMR (500 MHz, NH₂NH₂·H₂O): δ = 16.22 (s, 2H), 7.36–7.25 (m, 12H), 7.03 (d, *J* = 6.7 Hz, 8H), 5.15 ppm (s, 4H); ¹³C NMR (125 MHz, NH₂NH₂·H₂O): δ = 156.6 (Cq), 145.2 (Cq), 139.8 (Cq), 131.6 (CH), 129.1 (CH), 127.6 (CH), 127.2 (CH), 117.4 (Cq), 110.2 (Cq), 95.5 ppm (Cq). IR (PPh₄ salt, ATR): ν̃ = 3060, 2193, 1672, 1588, 1485, 1437, 1337, 1164, 1108, 997, 800, 753, 722, 688, 463 cm⁻¹; UV-vis (hydrazinium salt, NH₂NH₂·H₂O): λ_{max} (relative intensity) = 404 (0.65), 427 (0.95), 535 (0.60), 579 (1.0), 778 nm (shoulder, 0.02).

Reduction of CF₃-CNTPP and isolation of (PPh₄)₂[CF₃-CNIph]

To a solution of CF₃-CNTPP in DMSO (or [D₆]DMSO), a few drops of NH₂NH₂·H₂O were added until the color of the solution changed rapidly to reddish-purple. ¹H NMR and UV-vis/NIR analyses revealed the quantitative formation of [CF₃-CNIph]²⁻, potentially as a hydrazinium salt. For the isolation of [CF₃-CNIph]²⁻, CF₃-CNTPP (20.8 mg, 21.1 μmol) was dissolved in 1.25 mL of NH₂NH₂·H₂O/DMSO (1:4 v/v). A saturated solution of tetraphenylphosphonium bromide in methanol was gently poured into the resulting solution and left to stand for 1 day. Then, the precipitated microcrystals of (PPh₄)₂[CF₃-CNIph] were collected by filtration and dried under vacuum to afford (PPh₄)₂[CF₃-CNIph] as brown microcrystals (20.4 mg, 12.2 μmol, 58%). M.p. (PPh₄ salt): >300 °C; ¹H NMR (hydrazinium salt, 500 MHz, [D₆]DMSO + 1% NH₂NH₂·H₂O): δ = 16.49 (s, 2H), 7.50 (d, *J* = 8.1 Hz, 8H), 7.09 (d, *J* = 7.9 Hz, 8H), 4.99 ppm (d, *J* = 1.7 Hz, 4H); ¹³C NMR (hydrazinium salt, 125 MHz, [D₆]DMSO + 1% NH₂NH₂·H₂O): δ = 154.1 (Cq), 144.9 (Cq), 144.4 (Cq), 131.8 (CH), 133.5 (CH), 127.1 (q, ³*J*_{C-F} = 31.2 Hz, -CCF₃), 126.6 (CH), 125.5 (q, ⁴*J*_{C-F} = 3.6 Hz, CH), 124.5 (q, ²*J*_{C-F} = 272.3 Hz, -CF₃), 115.9 (Cq), 109.4 (Cq), 97.1 ppm (Cq); IR (PPh₄ salt, ATR): ν̃ = 3401 (NH), 3065, 3055, 2173 (CN), 1606, 1482, 1437, 1423, 1406, 1321, 1221, 1184, 1167, 1097, 1063, 1018, 995, 968, 950, 857, 835, 807, 779, 753, 720, 689, 669 cm⁻¹; UV-Vis/NIR (hydrazinium salt, DMSO + 1% NH₂NH₂·H₂O): λ_{max} (Log ε) = 353 (shoulder, 4.36), 376 (4.47), 405 (4.66), 428 (4.84), 499 (shoulder, 4.27), 537 (4.64), 581 (4.84), 726 (shoulder, 3.13), 824 nm (shoulder, 2.94); Elemental analysis (PPh₄ salt) calcd (%) for C₁₀₀H₆₂N₈P₂F₁₂·H₂O: C 71.34; H 3.83; N 6.66; found: C 71.50; H 3.87; N 6.78.

2.4.3 NMR Spectra of New Compounds

7,8,17,18-Tetrabromo-5,10,15,20-tetrakis(4-trifluoromethylphenyl)porphyrin

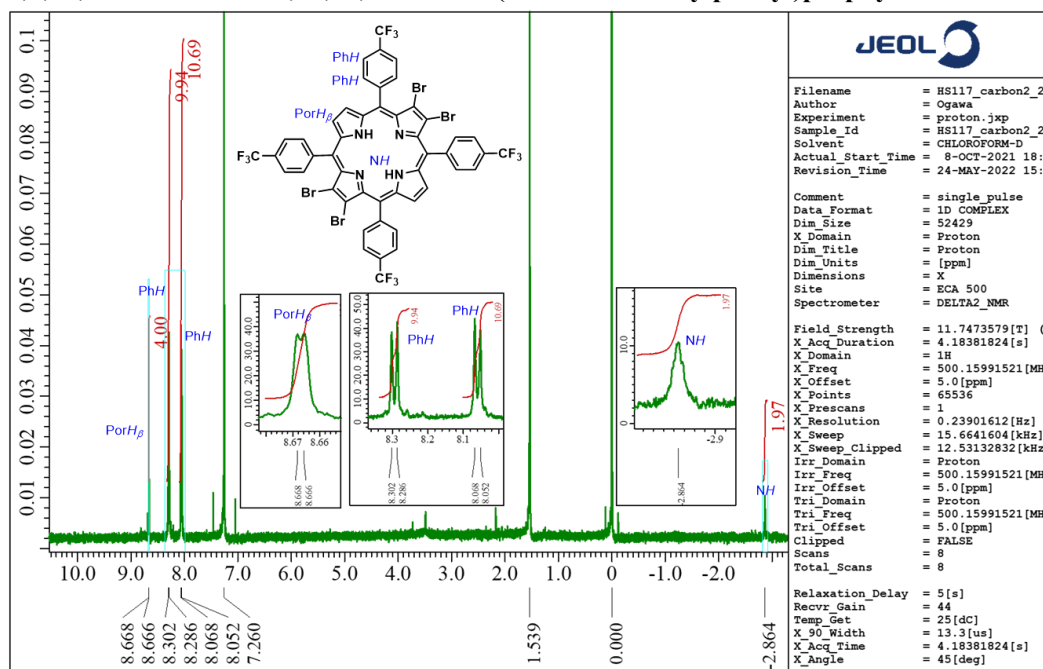


Figure E2.1 ¹H NMR spectrum in CDCl₃.

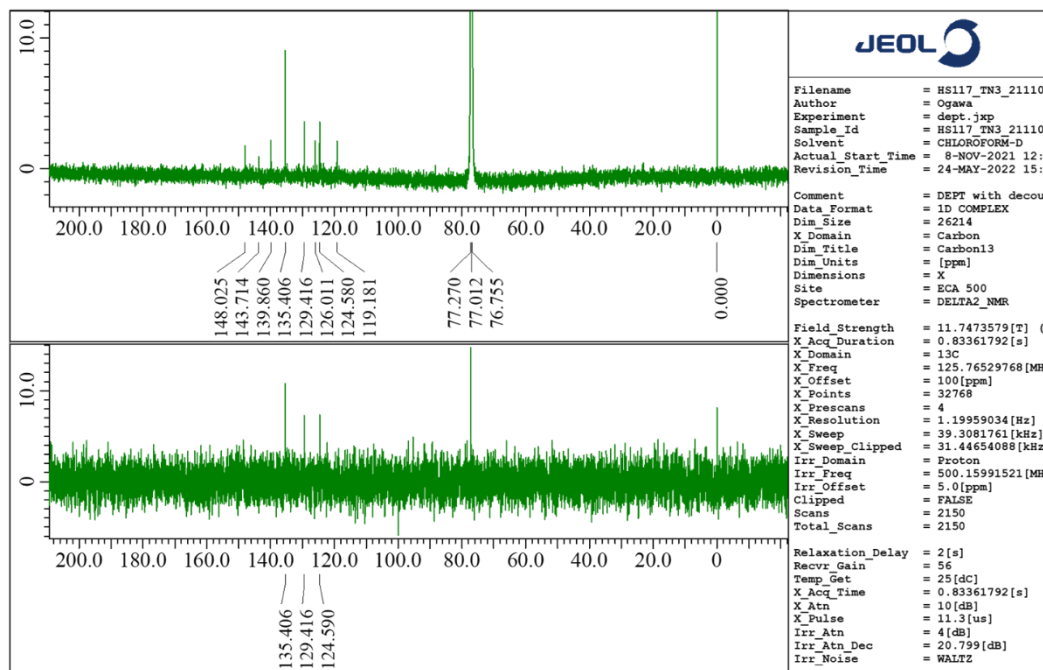


Figure E2.2 ¹³C NMR (above) and dept135 (down) spectra in CDCl₃.

[7,8,17,18-Tetrabromo-5,10,15,20-tetrakis(4-trifluoromethylphenyl)porphyrinato]nickel(II)

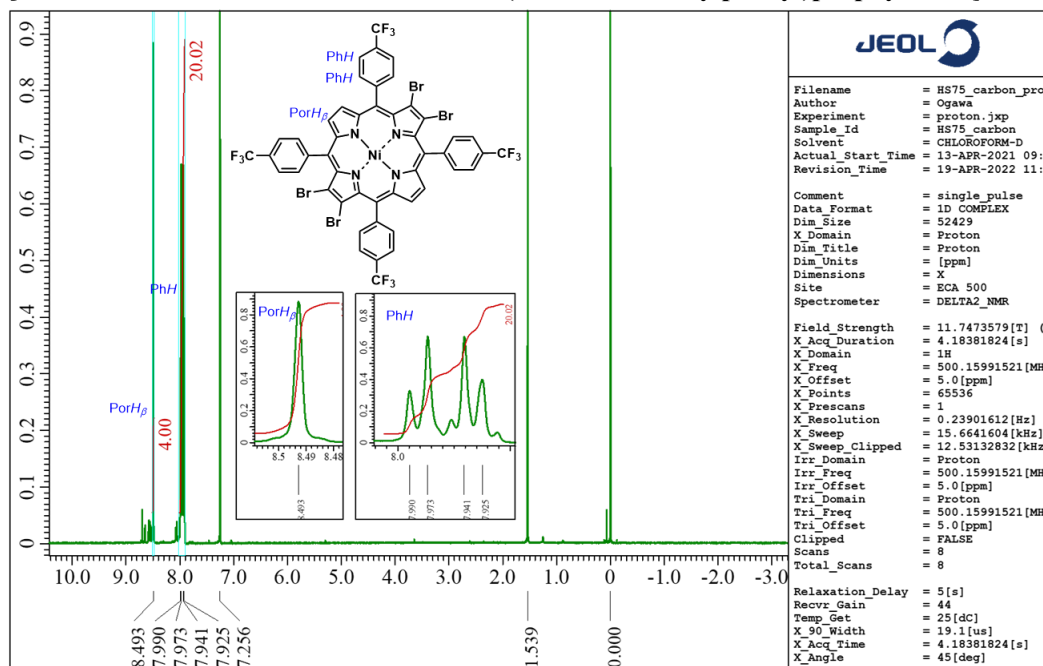


Figure E2.3 ¹H NMR spectrum in CDCl₃.

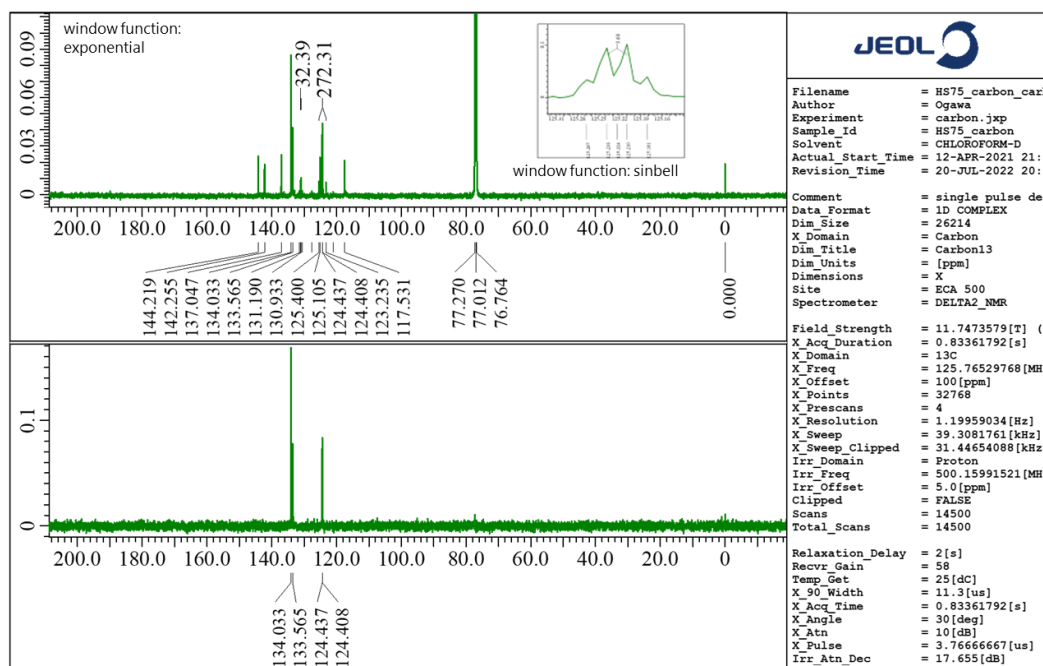


Figure E2.4 ¹³C NMR (above) and dept135 (down) spectra in CDCl₃.

[7,8,17,18-Tetracyano-5,10,15,20-tetrakis(4-trifluoromethylphenyl)porphyrinato]nickel(II)

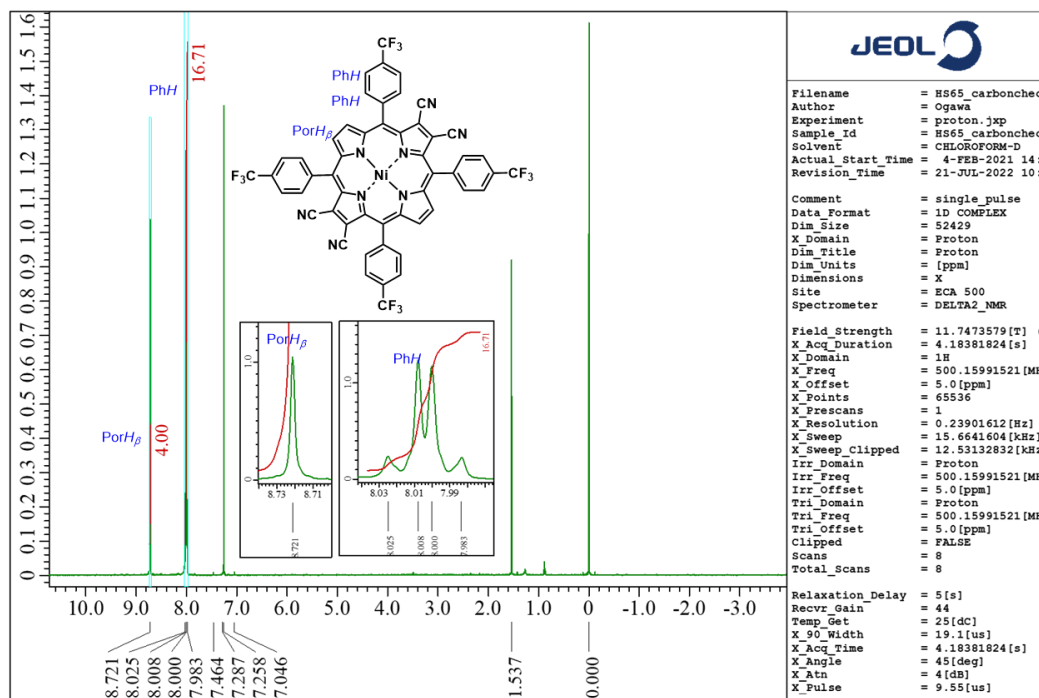


Figure E2.5 ¹H NMR spectrum in CDCl₃.

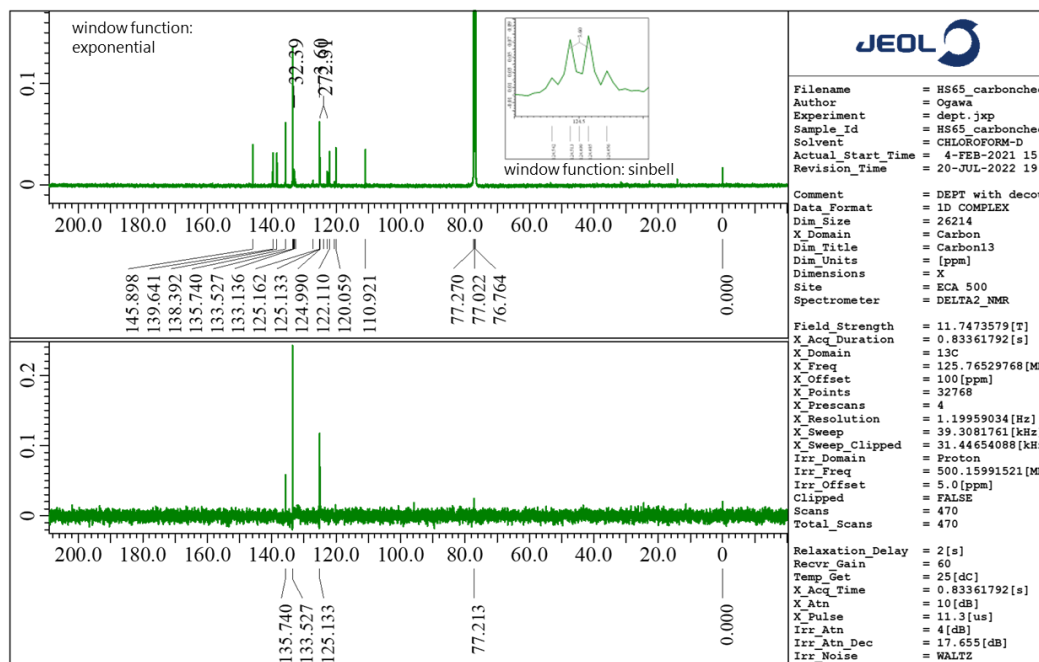


Figure E2.6 ¹³C NMR (above) and dept135 (down) spectra in CDCl₃.

7,8,17,18-Tetracyano-5,10,15,20-tetrakis(4-trifluoromethylphenyl)porphyrin (CF₃-CNTPP)

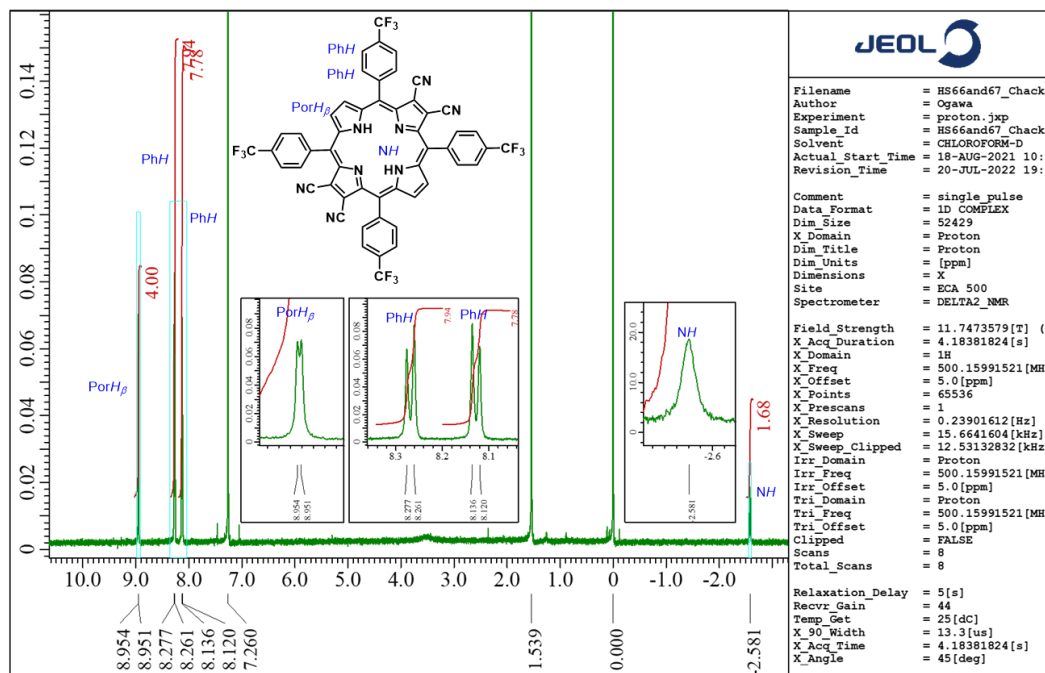


Figure E2.7 ¹H NMR spectrum in CDCl₃.

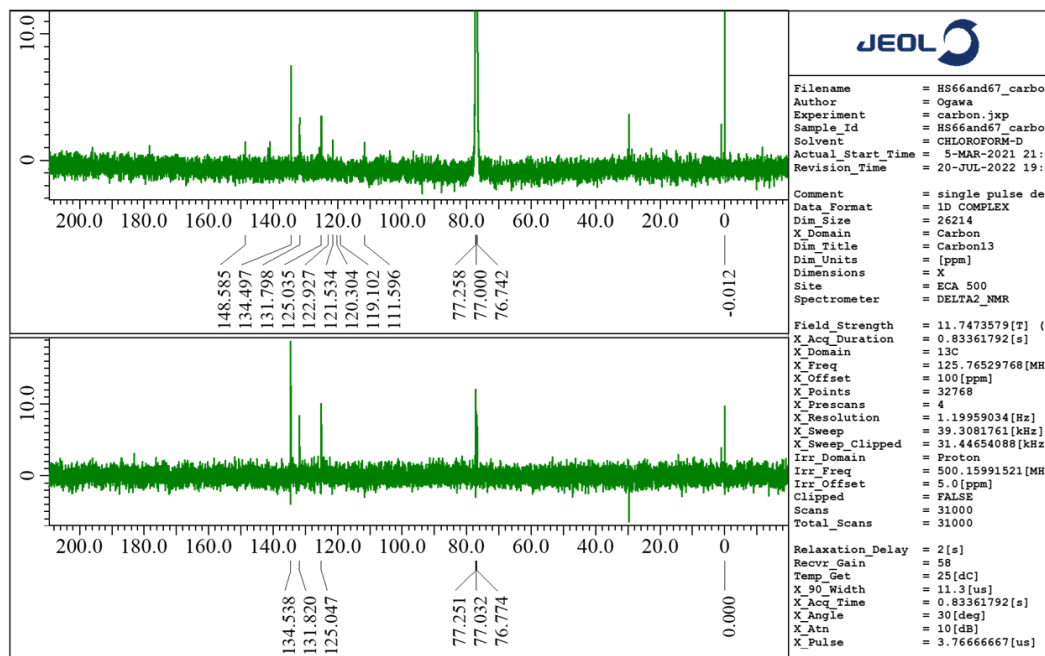


Figure E2.8 ¹³C NMR (above) and dept135 (down) spectra in CDCl₃.

7,8,17,18-Tetracyano-5,10,15,20-tetrakis(4-trifluoromethylphenyl)isophlorin ($[\text{CF}_3\text{-CNIph}]^{2-}$)

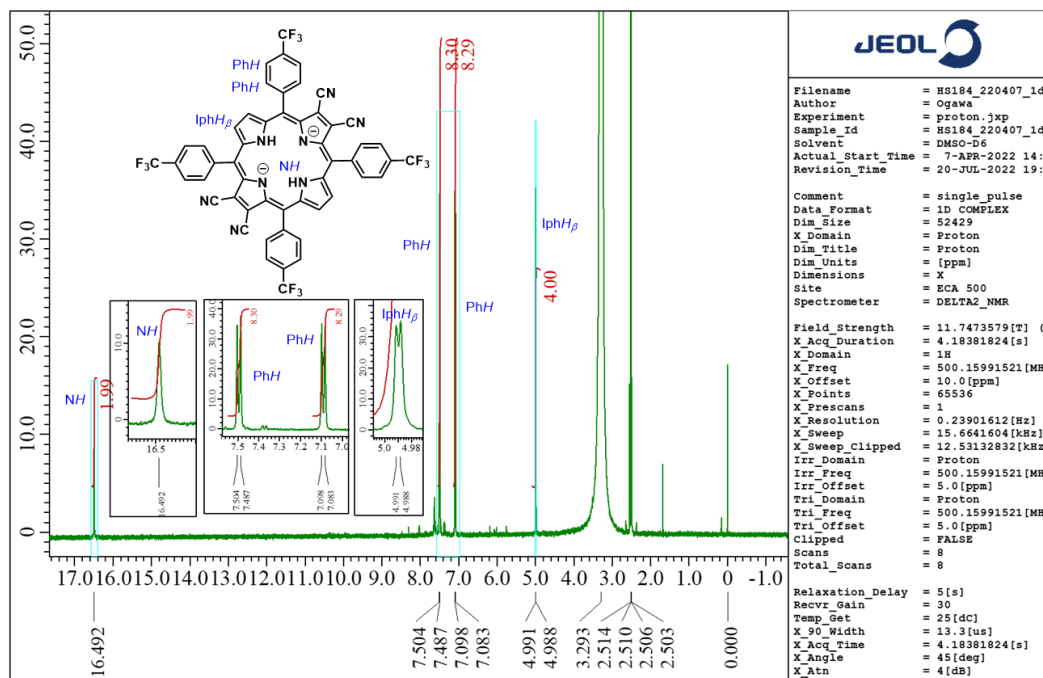


Figure E2.9 ^1H NMR spectrum in $[\text{D}_6]\text{DMSO}$.

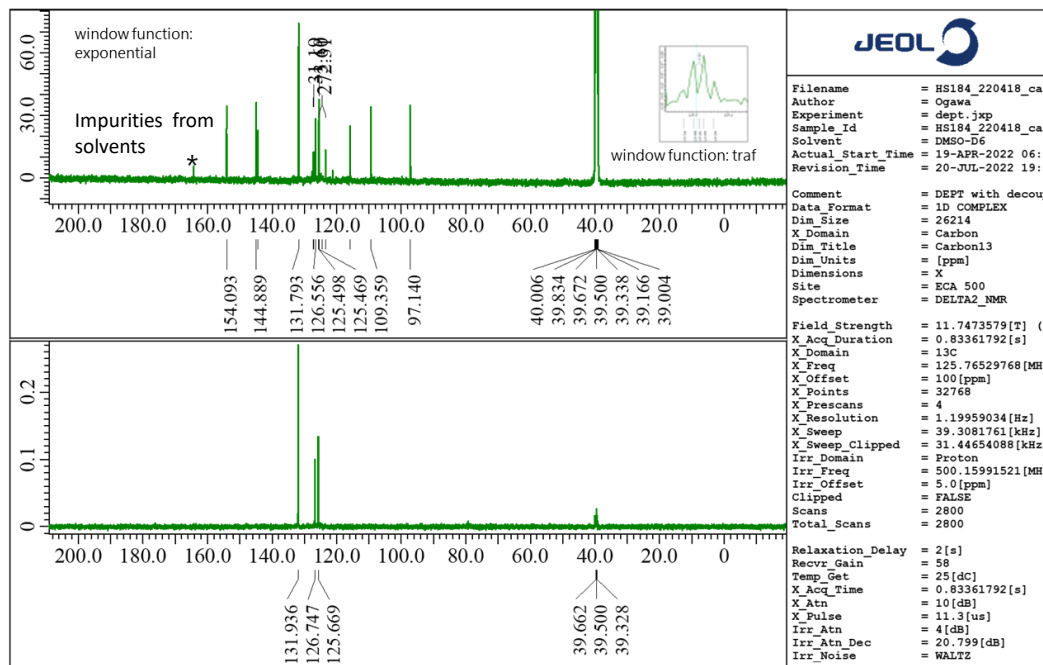


Figure E2.10 ^{13}C NMR (above) and dept135 (down) spectra in $[\text{D}_6]\text{DMSO}$.

7,8,17,18-Tetracyano-5,10,15,20-tetraphenylisophlorin ([CNlph]²⁻)

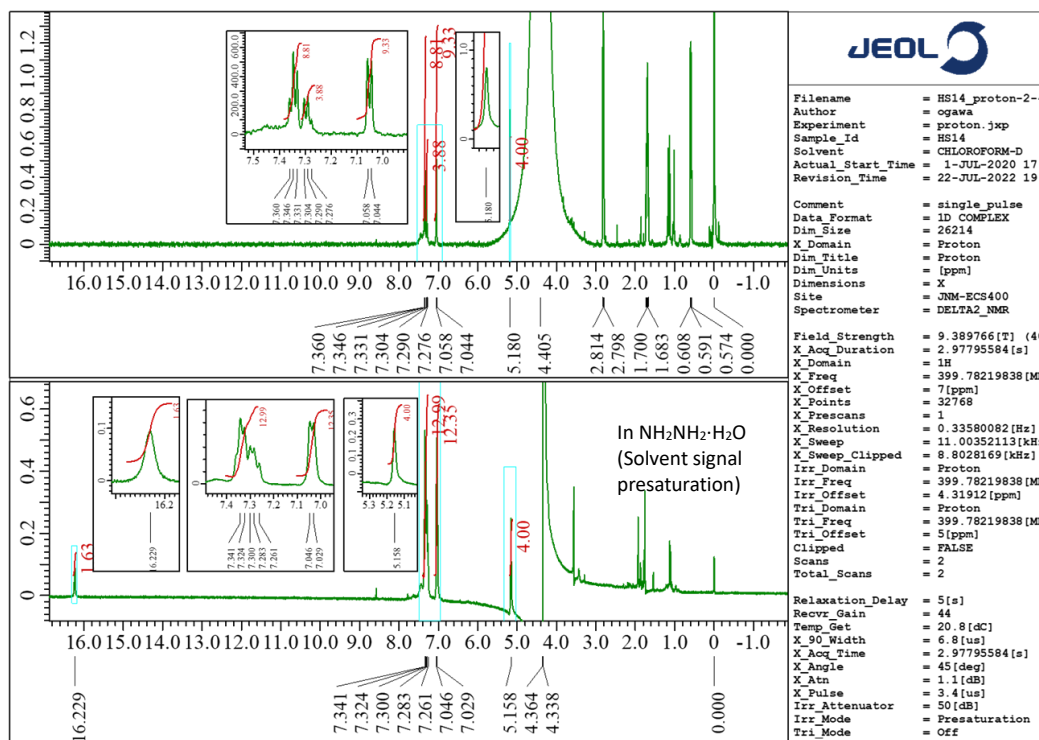


Figure E2.11 ¹H NMR spectra in ND₂ND₂·D₂O (above) and in NH₂NH₂·H₂O (above)

2.4.4 X-ray Crystal Structure Determinations

Single-crystal X-ray diffraction data were collected on a Rigaku XtaLAB Synergy Custom diffractometer using multilayer mirror monochromated Mo-K_α radiation ($\lambda = 0.71075$ Å) by the ω scan mode. The crystal was cooled by a stream of cold N₂ gas. Collection, indexing, peak integration, cell refinement, and scaling of the diffraction data were performed using CrysAlisPro 1.171.40.75a software (Rigaku OD, 2020). The data were corrected for Lorentz and polarization effects, and empirical absorption correction was applied. The structures were solved using SHELXT^[38] programs and refined by full-matrix least-squares calculations on F^2 (SHELXL).^[39] All non-hydrogen atoms were modeled anisotropically. All hydrogen atoms were placed in idealized positions and refined using a riding model [$U_{\text{iso}}(\text{H}) = 1.2U_{\text{eq}}(\text{C})$]. The crystallographic data is summarized in Table E2.1. Deposition Numbers 2163534 (for (PPh₄)₂[CNlph]), and 2163533 (for (PPh₄)₂[CF₃-CNlph]) contain the supplementary crystallographic data for these crystals. Single crystals of (PPh₄)₂[CNlph] and (PPh₄)₂[CF₃-CNlph] suitable for X-ray diffraction study were obtained by slow diffusion of tetraphenylphosphonium bromide in methanol into a solution of [CNlph]²⁻ and [CF₃-CNlph]²⁻ (just reduced by NH₂NH₂·H₂O) in methanol.

Table E2.1 Crystallographic data

	(PPh ₄) ₂ [CNlph]·(CH ₃ OH) (H ₂ O)	(PPh ₄) ₂ [CF ₃ -CNlph]
CCDC No.	2163534	2163533
empirical formula	C ₉₇ H ₇₂ N ₈ O ₂ P ₂	C ₁₀₀ H ₆₂ F ₁₂ N ₈ P ₂
formula weight	1443.56	1665.51
temperature / K	153	193
crystal system	Monoclinic	Monoclinic
space group	<i>P</i> 2 ₁ /c	<i>P</i> 2/c
<i>a</i> / Å	20.4901(6)	16.1593(3)
<i>b</i> / Å	13.9677(3)	8.7588(2)
<i>c</i> / Å	26.7395(8)	28.5909(7)
<i>a</i> / deg	90	90
<i>b</i> / deg	97.019(3)	90.720(2)
<i>g</i> / deg	90	90
<i>V</i> / Å ³	7595.5(4)	4046.32(15)
<i>Z</i>	4	2
<i>D</i> (calcd) / g cm ⁻³	1.262	1.367
<i>m</i> / mm ⁻¹	0.116	0.138
<i>F</i> (000)	3024	1712
crystal size / mm ³	0.15 × 0.05 × 0.02	0.24 × 0.05 × 0.02
<i>q</i> range for data collection / deg	1.535 to 30.682	1.890 to 30.612
index ranges	-28 ≤ <i>h</i> ≤ 25, -16 ≤ <i>k</i> ≤ 19, -36 ≤ <i>l</i> ≤ 33	-20 ≤ <i>h</i> ≤ 22, -11 ≤ <i>k</i> ≤ 11, -36 ≤ <i>l</i> ≤ 37
reflections collected	70879	47688
independent reflections	18937 [R(int) = 0.0965]	10305 [R(int) = 0.0396]
completeness	100.0%	100.0%
data / restraints / parameters	18937 / 43 / 993	10305 / 10 / 563
GOF on <i>F</i> ²	0.967	1.153
final <i>R</i> indices [<i>I</i> > 2σ(<i>I</i>)] ^a	<i>R</i> ₁ = 0.0676, <i>wR</i> ₂ = 0.1576	<i>R</i> ₁ = 0.0590, <i>wR</i> ₂ = 0.1636
<i>R</i> indices (all data) ^a	<i>R</i> ₁ = 0.1280, <i>wR</i> ₂ = 0.1825	<i>R</i> ₁ = 0.0927, <i>wR</i> ₂ = 0.1781
largest diff. peak and hole / e·Å ⁻³	0.510 and -0.468	1.387 and -0.437

^a $R_1 = \sum ||F_o| - |F_c|| / \sum |F_o|$, $wR_2 = [\sum [w(F_o^2 - F_c^2)^2] / \sum w(F_o^2)^2]^{1/2}$.

2.4.5 DFT Calculations

All calculations except for AICD were carried out using the Gaussian 16 program package (Revision C.01).^[40] The coordinates of the optimized structure can be found in the supporting information of the foundational papers. Geometries of all models were optimized by the DFT method at the B3LYP/6-31+G(d,p) level. For the coordinates of the optimized structure, see pp. S10–S26 (in https://chemistry-europe.onlinelibrary.wiley.com/action/downloadSupplement?doi=10.1002%2Fejoc.202200747&file=ejoc202200747-sup-0001-misc_information.pdf). Frequency calculations were performed to confirm that the optimized geometries were not in the saddle points but stable points.

Nucleus-independent chemical shifts (NICS) values were calculated at the GIAO-HF/6-311+G(d,p) level. The anisotropy of the current-induced density (ACID) calculations was performed using the Gaussian 09 program package (Revision E.01) at the B3LYP/6-31+G(d,p) level using the CSGT method and analyzed using the AICD 2.0.0 program.

Table E2.2 Summary of the TDDFT calculation of [CNlph]²⁻ (vacuum).

No.	Energy (cm ⁻¹)	Wavelength (nm)	Osc. Strength	Major contribution
1	9495.565	1053.123	0	HOMO->LUMO (100%)
2	15113.22	661.6725	0.3727	H-1->LUMO (13%), HOMO->L+1 (87%)
3	19915.44	502.1229	0.0088	HOMO->L+3 (77%), HOMO->L+7 (20%)
4	19966.25	500.8451	0.0123	HOMO->L+2 (73%), HOMO->L+6 (20%)
5	20342.92	491.5716	0.0037	HOMO->L+5 (52%), HOMO->L+9 (41%)
6	20389.7	490.4438	0	HOMO->L+4 (51%), HOMO->L+8 (47%)
7	20400.18	490.1917	0.0821	HOMO->L+2 (19%), HOMO->L+6 (78%)
8	20870.4	479.1474	0	HOMO->L+4 (45%), HOMO->L+8 (46%)
9	20926.86	477.8547	0.0054	HOMO->L+3 (18%), HOMO->L+7 (79%)
10	21118.01	473.5294	0.1353	H-1->LUMO (11%), HOMO->L+5 (10%), HOMO->L+9 (25%), HOMO->L+11 (53%)
11	21149.47	472.8251	0.0201	HOMO->L+10 (91%)
12	21373.69	467.8649	0.0062	HOMO->L+5 (38%), HOMO->L+9 (25%), HOMO->L+11 (36%)
13	21379.34	467.7413	0.0016	HOMO->L+12 (95%)
14	21393.05	467.4415	0	HOMO->L+13 (92%)
15	22042.33	453.6726	0	H-1->L+1 (96%)
16	22391.56	446.5968	1.3339	H-1->LUMO (72%), HOMO->L+1 (14%)
17	24064.36	415.5523	0.2692	H-2->LUMO (93%)
18	24482.96	408.4473	0.0008	HOMO->L+14 (97%)
19	24489.41	408.3397	0.0034	HOMO->L+15 (89%)
20	25093.52	398.5092	0	HOMO->L+16 (98%)
21	25478.25	392.4917	0.0003	H-2->L+1 (37%), HOMO->L+19 (52%)
22	25683.92	389.3487	0.0002	HOMO->L+18 (97%)
23	26042.84	383.9828	0.0003	HOMO->L+17 (99%)
24	26964.73	370.8548	0.0024	H-3->LUMO (91%)
25	27176.85	367.9602	0	HOMO->L+20 (92%)
26	27340.58	365.7567	0.0564	H-4->LUMO (98%)
27	27597.07	362.3574	0	HOMO->L+21 (98%)
28	27629.33	361.9342	0.0896	H-2->L+1 (45%), HOMO->L+19 (35%)
29	28239.89	354.109	0.0032	HOMO->L+22 (95%)
30	28927.07	345.6969	0.0549	H-1->L+3 (70%), H-1->L+7 (26%)

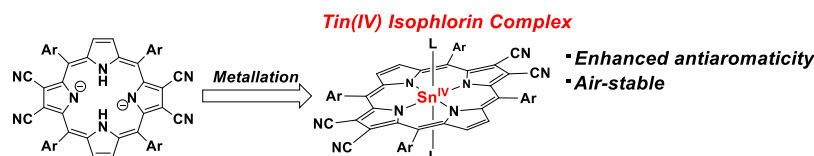
2.5 References

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- [1] B. K. Reddy, A. Basavarajappa, M. D. Ambhore, V. G. Anand, *Chem. Rev.* **2017**, *117*, 3420–3443.
- [2] P. Pushpanandan, M. Ravikanth, *Chem. Rec.* **2022**, *22*, e202200144.
- [3] R. B. Woodward, *Angew. Chem.* **1960**, *72*, 651–662.
- [4] C. Liu, D.-M. Shen, Q.-Y. Chen, *J. Am. Chem. Soc.* **2007**, *129*, 5814–5815.
- [5] Q.-Y. Chen, X.-G. Chen, C. Liu, D.-M. Shen, *Synthesis (Mass.)* **2009**, *2009*, 3860–3868.
- [6] W. Suzuki, H. Kotani, T. Ishizuka, Y. Shiota, K. Yoshizawa, T. Kojima, *Angew. Chem. Int. Ed.* **2018**, *57*, 1973–1977.
- [7] W. Suzuki, H. Kotani, T. Ishizuka, T. Kojima, *J. Am. Chem. Soc.* **2019**, *141*, 5987–5994.
- [8] R. Cosmo, C. Kautz, K. Meerholz, J. Heinze, K. Müllen, *Angew. Chem., Int. Ed. Engl.* **1989**, *28*, 604–607.
- [9] R. Bachmann, F. Gerson, G. Gescheidt, E. Vogel, *J. Am. Chem. Soc.* **1992**, *114*, 10855–10860.
- [10] J. A. Cissell, T. P. Vaid, A. L. Rheingold, *J. Am. Chem. Soc.* **2005**, *127*, 12212–12213.
- [11] J. A. Cissell, T. P. Vaid, G. P. A. Yap, *J. Am. Chem. Soc.* **2007**, *129*, 7841–7847.
- [12] A. Weiss, M. C. Hodgson, P. D. W. Boyd, W. Siebert, P. J. Brothers, *Chem. Eur. J.* **2007**, *13*, 5982–5993.
- [13] J. S. Reddy, V. G. Anand, *J. Am. Chem. Soc.* **2008**, *130*, 3718–3719.
- [14] T. P. Vaid, *J. Am. Chem. Soc.* **2011**, *133*, 15838–15841.
- [15] S. P. Panchal, S. C. Gadekar, V. G. Anand, *Angew. Chem. Int. Ed Engl.* **2016**, *55*, 7797–7800.
- [16] S. P. Panchal, S. C. Gadekar, V. G. Anand, *Angew. Chem. Weinheim Bergstr. Ger.* **2016**, *128*, 7928–7931.
- [17] K. Yamashita, K. Nakajima, Y. Honda, T. Ogawa, *Chem. Eur. J.* **2020**, *26*, 3633–3640.
- [18] H. Duval, V. Bulach, J. Fischer, R. Weiss, *Inorg. Chem.* **1999**, *38*, 5495–5501.
- [19] Y. Song, R. E. Haddad, S.-L. Jia, S. Hok, M. M. Olmstead, D. J. Nurco, N. E. Schore, J. Zhang, J.-G. Ma, K. M. Smith, S. Gazeau, J. Pécaut, J.-C. Marchon, C. J. Medforth, J. A. Shelnutt, *J. Am. Chem. Soc.* **2005**, *127*, 1179–1192.
- [20] X. Ke, P. Yadav, L. Cong, R. Kumar, M. Sankar, K. M. Kadish, *Inorg. Chem.* **2017**, *56*, 8527–8537.
- [21] M. Sankar, P. Bhyrappa, *Chem. Phys. Lett.* **2019**, *730*, 643–648.
- [22] P. Bhyrappa, M. Sankar, B. Varghese, *Inorg. Chem.* **2006**, *45*, 4136–4149.
- [23] P. Bhyrappa, C. Arunkumar, B. Varghese, *Inorg. Chem.* **2009**, *48*, 3954–3965.
- [24] J. D. Megiatto Jr, A. Antoniuk-Pablant, B. D. Sherman, G. Kodis, M. Gervaldo, T. A. Moore, A. L. Moore, D. Gust, *Proc. Natl. Acad. Sci. U. S. A.* **2012**, *109*, 15578–15583.
- [25] S. Pillai, J. Ravensbergen, A. Antoniuk-Pablant, B. D. Sherman, R. van Grondelle, R. N. Frese, T. A. Moore, D. Gust, A. L. Moore, J. T. M. Kennis, *Phys. Chem. Chem. Phys.* **2013**, *15*, 4775–4784.

- [26] J. Ravensbergen, A. Antoniuk-Pablant, B. D. Sherman, G. Kodis, J. D. Megiatto Jr, D. D. Méndez-Hernández, R. N. Frese, R. van Grondelle, T. A. Moore, A. L. Moore, D. Gust, J. T. M. Kennis, *J. Phys. Chem. B* **2015**, *119*, 12156–12163.
- [27] R. Kumar, N. Chaudhri, M. Sankar, *Dalton Trans.* **2015**, *44*, 9149–9157.
- [28] K. Karunanithi, P. Bhyrappa, *Inorganica Chim. Acta* **2015**, *427*, 41–51.
- [29] H. J. Callot, *Tetrahedron Lett.* **1973**, *14*, 4987–4990.
- [30] A. Ghosh, *The Porphyrin Handbook*, Academic Press, San Diego, CA, **2000**.
- [31] J. Kruszewski, T. M. Krygowski, *Tetrahedron Lett.* **1972**, *13*, 3839–3842.
- [32] T. M. Krygowski, H. Szatyłowicz, O. A. Stasyuk, J. Dominikowska, M. Palusiak, *Chem. Rev.* **2014**, *114*, 6383–6422.
- [33] D. Geuenich, K. Hess, F. Köhler, R. Herges, *Chem. Rev.* **2005**, *105*, 3758–3772.
- [34] P. von R. Schleyer, C. Maerker, A. Dransfeld, H. Jiao, N. J. R. van Eikema Hommes, *J. Am. Chem. Soc.* **1996**, *118*, 6317–6318.
- [35] Z. Chen, C. S. Wannere, C. Corminboeuf, R. Puchta, P. von R. Schleyer, *Chem. Rev.* **2005**, *105*, 3842–3888.
- [36] Y. Saegusa, T. Ishizuka, K. Komamura, S. Shimizu, H. Kotani, N. Kobayashi, T. Kojima, *Phys. Chem. Chem. Phys.* **2015**, *17*, 15001–15011.
- [37] H. Sugimura, K. Nakajima, K. Yamashita, T. Ogawa, *Eur. J. Org. Chem.* **2022**, e202200747.
- [38] G. M. Sheldrick, *Acta Crystallogr. A* **2008**, *64*, 112–122.
- [39] G. M. Sheldrick, *Acta Crystallogr. A Found. Adv.* **2015**, *71*, 3–8.
- [40] M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, G. Scalmani, V. Barone, G. A. Petersson, H. Nakatsuji, X. Li, M. Caricato, A. V. Marenich, J. Bloino, B. G. Janesko, R. Gomperts, B. Mennucci, H. P. Hratchian, J. V. Ortiz, A. F. Izmaylov, J. L. Sonnenberg, D. Williams-Young, F. Ding, F. Lipparini, F. Egidi, J. Goings, B. Peng, A. Petrone, T. Henderson, D. Ranasinghe, V. G. Zakrzewski, J. Gao, N. Rega, G. Zheng, W. Liang, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, T. Vreven, K. Throssell, J. A. Montgomery Jr, J. E. Peralta, F. Ogliaro, M. J. Bearpark, J. J. Heyd, E. N. Brothers, K. N. Kudin, V. N. Staroverov, T. A. Keith, R. Kobayashi, J. Normand, K. Raghavachari, A. P. Rendell, J. C. Burant, S. S. Iyengar, J. Tomasi, M. Cossi, J. M. Millam, M. Klene, C. Adamo, R. Cammi, J. W. Ochterski, R. L. Martin, K. Morokuma, O. Farkas, J. B. Foresman, Fox, D. J. Gaussian, Inc., *Gaussian16, Revision C.01*, **2016**.

Chapter 3.

Isophlorin Metal Complexes: Enhanced Antiaromaticity through Metal Complexation



Abstract: Isophlorins, which are two-electron reduced porphyrins, have garnered significant interest because of their potential antiaromaticity and unique electronic properties. However, the isolation of stable antiaromatic isophlorins remains challenging because they are prone to oxidation or reduction to the corresponding aromatic molecules, or are structurally distorted, resulting in loss of antiaromaticity. Here, the synthesis and characterization of a Sn(IV) β -tetracyanoisophlorin complex was reported, obtained through two-electron reduction of the corresponding Sn(IV) β -tetracyanoporphyrin complex. This Sn(IV) complex exhibits enhanced antiaromaticity owing to its highly planar structure, facilitated by the central Sn atom. X-ray crystal diffraction analysis revealed that the Sn(IV) isophlorin complex contains two methoxy groups as axial ligands and that it exists as a divalent anion, demonstrating the oxophilic nature of the Sn(IV) isophlorin complexes. Notably, this Sn(IV) isophlorin complex is stable under air, distinguishing it from previously reported Si(IV) and Ge(IV) isophlorin complexes without cyano groups. This study thus presents the first isolation of an air-stable metal complex of antiaromatic isophlorin, opening new possibilities for exploring the unique properties of antiaromatic porphyrinoids for various applications, including catalysis and materials science.

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3.1 Introduction

In Chapter 2, antiaromatic isophlorins without metalation or core modification were successfully synthesized.^[1] The significance of this work is that the isolation was achieved by optimizing the molecular structure and increasing the reduction potential through the introduction of electron-withdrawing substituents such as CN groups. Previously reported stable antiaromatic isophlorins were often synthesized by substituting the nitrogen atom within the ring with oxygen or sulfur atoms to reduce the steric hindrance of the inner NHs.^[2–4] However, the isophlorins reported in Chapter 2, had the planer structure and exhibited antiaromaticity despite having four nitrogen atoms, which is achieved through molecular design involving the introduction of electron-withdrawing substituents. This isophlorins, containing four nitrogen atoms, can coordinate with metal ions. This suggests the possibility of adjusting various physical properties and applications by introducing metals.

Porphyrin metal complexes are widely used as pigments and catalysts, including chlorophyll and heme, which are present in living organisms.^[5] Isophlorin–metal complexes have been studied electrochemically, including measurements on the Zn complex of meso-tetrarylporphyrin by Müllen et al. in 1989.^[6] However, only Si(IV) and Ge(IV) isophlorin complexes have been successfully isolated.^[7–9] These complexes are highly sensitive to air and challenging to handle under atmospheric conditions.

Although Group 14 elements can adopt both divalent and tetravalent oxidation states, the stability of the tetravalent state decreases in the order Si > Ge > Sn. For Sn, the inert pair effect stabilizes the divalent state more significantly than for Si or Ge.^[7–9] Consequently, when Sn^{IV}(tpp) (tpp = tetraphenylporphyrinato dianion) is reduced, metal reduction is favored over porphyrin reduction, which has previously prevented the isolation of Sn isophlorin complexes.^[9] Sn(IV)–porphyrin complexes have been studied extensively, particularly in photocatalysis and photodynamic therapy.^[10,11] They are significantly easier to synthesize than other Group 14 metal–porphyrin complexes (Si(IV) and Ge(IV)) and exhibit higher reduction potentials than many other metal–porphyrin complexes.^[12] I hypothesized that using the β -tetracyanoporphyrin as a ligand for Sn, which has a significantly higher reduction potential than TPP, might lead to selective ligand reduction and the formation of the desired isophlorin (Figure 3.1).

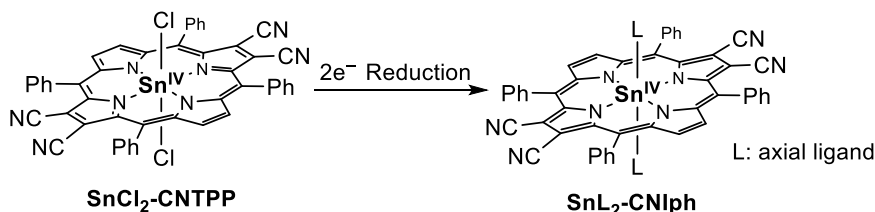
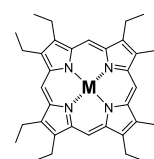


Figure 3.1 Synthetic scheme for tin(IV) complex of β -tetracyanoisophlorin.

To investigate the influence of metals on isophlorin metal complexes, the author also explored the synthesis of Zn(II) and Pd(II) complexes. Zn(II) and Pd(II) porphyrin complexes are known to have lower reduction potentials compared to their metal-free porphyrin or the porphyrin Sn(IV) complex (Table 3.1).^[12] The aim is to synthesize Sn(IV), Zn(II), and Pd(II) isophlorin complexes and investigate the correlation between their oxidation-reduction properties and the physical properties of isophlorin metal complexes.

Table 3.1 Redox potentials (V vs SCE) for octaethylporphyrin

metal	$E_{\text{ox}2}^{[a]}$	$E_{\text{ox}1}^{[a]}$	$E_{\text{red}1}^{[b]}$	$E_{\text{red}2}^{[b]}$
H ₂ (= metal free)	1.30	0.81	-1.46	-1.86
Zn(II)	1.02	0.63	-1.61	— ^[d]
Pd(II)	— ^[d]	0.82	-1.53 ^[c]	— ^[d]
Sn(IV)(OH) ₂	>1.4	>1.4	-0.90	-1.30



[a] In 0.01 M tetrabutylammonium hexafluorophosphate (TBAP) in butyronitrile. [b] In 0.01 M TBAP in DMSO. [c] In 0.01 M TBAP in DMF. [d] Not reported in reference.

Furthermore, by examining these Zn(II) and Pd(II) complexes, the study encompasses all three classifications of porphyrins proposed by Gouterman.^[13,14] He classified porphyrins based on their absorption spectra: normal porphyrins, hypso-porphyrins, and hyperporphyrins. Normal porphyrins exhibit an absorption spectrum resembling that of metal-free porphyrins. Hypso-porphyrins are blue-shifted compared to metal-free porphyrins, while hyperporphyrins are red-shifted. It is expected that if the Zn(II) complex can be synthesized, it would be classified as a normal porphyrin, while the Pd(II) complex would likely be a hypso-porphyrin. Zn(II) porphyrins are classified as normal porphyrins because Zn(II) forms a closed-shell structure with a d_{10} configuration. This means that the effect of Zn(II) on the electronic structure of the porphyrin, before and after metal introduction, is nearly negligible, resulting in an absorption spectrum that is roughly identical to that of metal-free porphyrins. On the other hand, with respect to hypso-porphyrins, the late transition metal Pd(II) has a d_8 configuration. Its absorption spectrum is believed to be blue-shifted due to backbonding, which elevates the porphyrin's LUMOs and contributes to a hypso-photic effect that lowers the a_{2u} HOMO levels in metalloporphyrins with less electropositive metal centers.^[15] Hyperporphyrins are characterized by the addition of additional metal orbitals to the four porphyrin frontier orbitals. When a low-oxidized metal (or element) fills the valence p orbitals with the appropriate symmetry, a metal-to-ligand charge transfer (MLCT) transition is typically observed. To synthesize hyperisophlorins, Sn(II) or Pb(II) complexes would be ideal.^[14] However, Sn(II) porphyrin complexes are inherently unstable, and only one successful synthesis has been reported to date. Therefore, although the author

In the ^1H NMR spectrum of $\text{SnCl}_2\text{-CNTPP}$ in CDCl_3 (Figure 3.3a), the signal for the β -proton was observed at 9.1 ppm as a singlet with small satellite peaks derived from the spin-spin couplings of ^{119}Sn and ^{117}Sn . The coupling constant $^4J_{\text{H-Sn}}$ was 15.2 Hz, which is in good agreement with that of $[\text{Sn}^{\text{IV}}(\text{tpp})\text{Cl}_2]$.^[18]

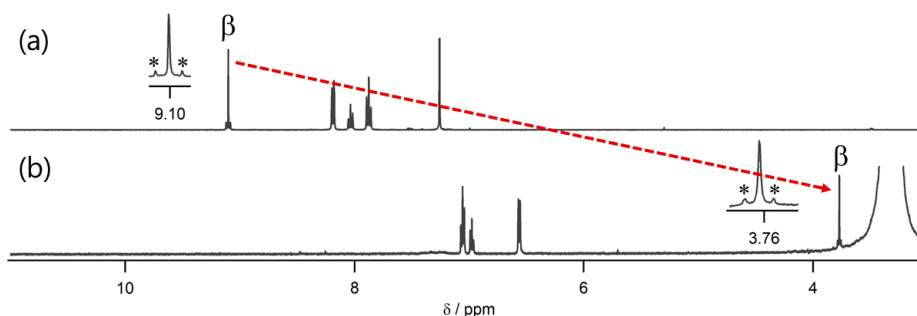


Figure 3.3 ^1H NMR spectra (500 MHz) showing the reduction of $\text{SnCl}_2\text{-CNTPP}$ to $\text{SnL}_2\text{-CNIph}$. (a) $\text{SnCl}_2\text{-CNTPP}$ in CDCl_3 at 25°C . (b) $\text{SnL}_2\text{-CNIph}$ was generated in situ by reduction with $\text{NH}_2\text{NH}_2\cdot\text{H}_2\text{O}$ (1 drop) in $[\text{D}_6]\text{DMSO}$ at 40°C . Asterisks indicate Sn satellite peaks.

The redox potentials of $\text{SnCl}_2\text{-CNTPP}$, Zn-CNTPP and Pd-CNTPP were determined using cyclic and differential pulse voltammetry (Figures 3.4–3.6 and Table 3.2).

Table 3.2 Half-wave potentials (V vs. Fc/Fc^+) of $\text{SnCl}_2\text{-CNTPP}$, Zn-CNTPP , Pd-CNTPP , CNTPP and $\text{CF}_3\text{-CNTPP}$ obtained from differential pulse voltammetry (DPV).

solvent	comp.	E_{ox1}	E_{red1}	E_{red2}	$E_{\text{red1}} - E_{\text{red2}}$
CH_2Cl_2	$\text{SnCl}_2\text{-CNTPP}$	1.42 ^[b]	−0.42	−0.87	0.45
	Zn-CNTPP	0.68 ^[b]	(−0.93) ^[b]	(−1.14) ^[b]	0.21
	Pd-CNTPP	1.17	−0.85	−1.30	0.45
	$\text{CNTPP}^{\text{[a]}}$	0.92	−0.75	−1.05	0.30
	$\text{CF}_3\text{-CNTPP}^{\text{[a]}}$	1.10	−0.60	−0.94	0.34
DMSO	$\text{SnCl}_2\text{-CNTPP}$	− ^[c]	−0.19	−0.60	0.41
	Zn-CNTPP	− ^[c]	−0.79	−1.24	0.45
	Pd-CNTPP	− ^[c]	−0.65	−1.11	0.46
	$\text{CF}_3\text{-CNTPP}^{\text{[a]}}$	− ^[c]	−0.47	−0.74	0.27

[a] Data from ref. 1. [b] Irreversible peak. [c] Out of the potential range.

In CH_2Cl_2 , $\text{SnCl}_2\text{-CNTPP}$ exhibited two reversible reduction waves at −0.42 V and −0.87 V, and an irreversible oxidation wave at 1.42 V. In DMSO, the reduction waves were positively shifted

by approximately 0.2 V, indicating that $\text{SnCl}_2\text{-CNTPP}$ was more easily reduced in polar solvents, similar to free bases CNTPP and $\text{CF}_3\text{-CNTPP}$.^[1] The second reduction potential of $\text{SnCl}_2\text{-CNTPP}$ (-0.60 V in DMSO) was more positively shifted than $\text{CF}_3\text{-CNTPP}$ (-0.74 V in DMSO). The difference between the second and first reduction potentials of $\text{SnCl}_2\text{-CNTPP}$ was 0.45 V in CH_2Cl_2 and 0.41 V in DMSO. These differences are larger than those of free bases CNTPP and $\text{CF}_3\text{-CNTPP}$, indicating the greater stability of the one-electron reduced form of $\text{SnCl}_2\text{-CNTPP}$.

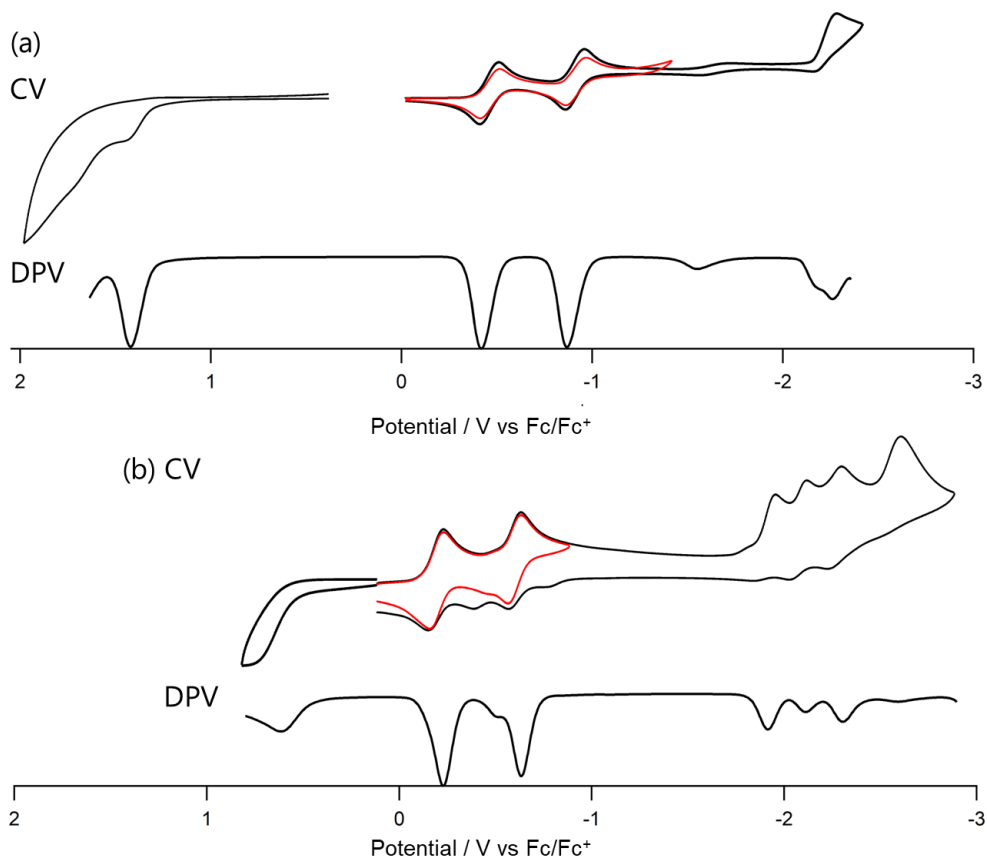


Figure 3.4 Cyclic and differential pulse voltammogram of (a) $\text{SnCl}_2\text{-CNTPP}$ in CH_2Cl_2 and (b) $\text{SnCl}_2\text{-CNTPP}$ in DMSO.

For the Zn-CNTPP , irreversible reduction potentials were observed at -0.93 V, -1.14 V, -1.54 V, and -1.82 V in CH_2Cl_2 , reversible oxidation peaks at 0.68 V and 1.34 V, and an irreversible oxidation peak at 1.07 V (Figure 3.5a). DPV revealed that the peak areas for the first and third oxidation potentials roughly coincide, suggesting that this is due to the porphyrin ring. However, because the porphyrin Zn complex can form a five-coordinate square pyramid form, various states are possible in the less polar CH_2Cl_2 solution, with no fixed axial ligand. Therefore, these three oxidation potential peaks may also represent potentials for porphyrin with different axial ligands, and it cannot be concluded that they represent one-electron or two-electron oxidation of the porphyrin ring. In DMSO, no oxidation potential was observed, but reversible reduction peaks were observed at -0.79

V and -1.24 V (Figure 3.5b). In DMSO, the polar solvent DMSO may coordinate with Zn, resulting in a single state and a clear CV peak. The reduction potential in DMSO was approximately 0.3 V lower than the -0.47 V and -0.74 V of $\text{CF}_3\text{-CNTPP}$ shown in the previous section, 2.2.1, making it less susceptible to reduction.

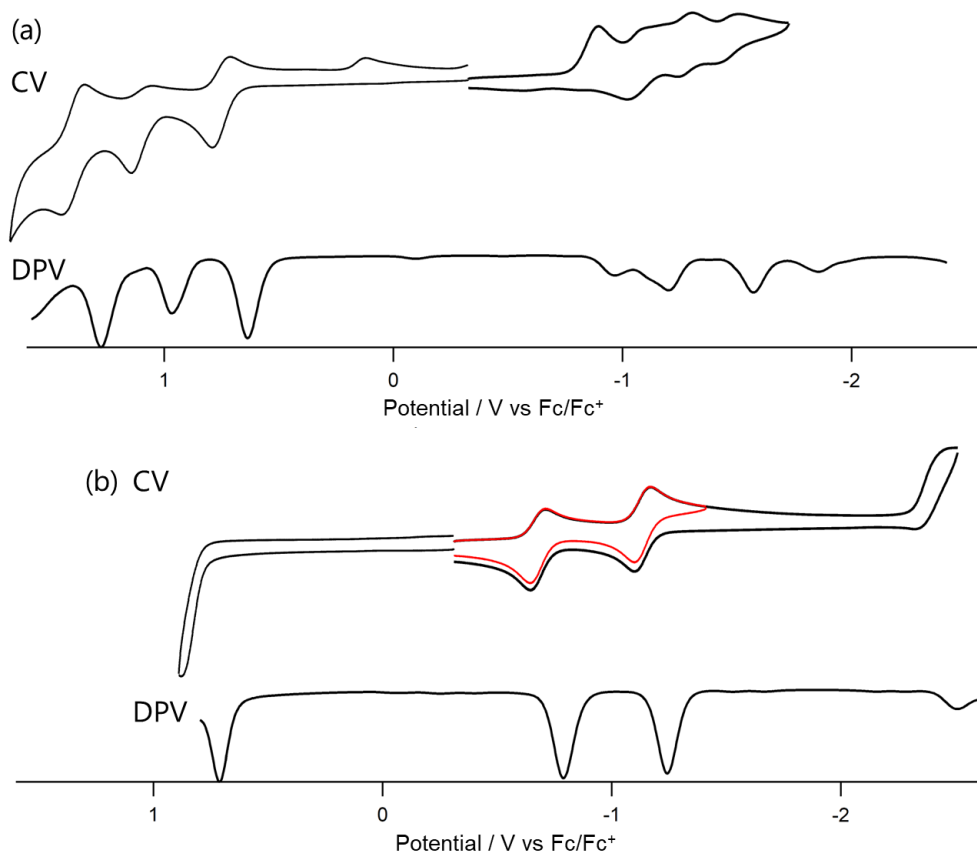


Figure 3.5 Cyclic and differential pulse voltammogram of (a) Zn-CNTPP in CH_2Cl_2 and (b) Zn-CNTPP in DMSO.

For Pd-CNTPP, reversible reduction potentials of -0.85 V and -1.30 V and reversible oxidation potential of 1.17 V were observed in CH_2Cl_2 (Figure 3.6a). In DMSO, reversible reduction potentials of -0.65 V and -1.11 V were observed (Figure 3.6b). Although the reduction potential increased by approximately 0.2 V in DMSO, making it more susceptible to reduction, it was still approximately 0.2 V less susceptible to reduction than $\text{CF}_3\text{-CNTPP}$. Comparing the Zn-CNTPP and Pd-CNTPP in DMSO, Pd-CNTPP exhibited a higher reduction potential of approximately 0.1 V, indicating its greater susceptibility to reduction. This is thought to be due to the lower electronegativity of Zn compared to Pd (Pauling's electronegativity: Pd: 2.20, Zn: 1.65).¹⁶ The greater the electronegativity of the central metal, the more easily the metalloporphyrin is reduced. This trend was also observed in the β -tetracyanoporphyrin metal complexes reported by Kadish et al.^[19]

Furthermore, the first reduction potentials of Zn-CNTPP and Pd-CNTPP were -0.79 V and -0.65 V, respectively, in DMSO. The second reduction potential of CF_3 -CNTPP was -0.74 V, a value similar to that of Zn-CNTPP and Pd-CNTPP. Therefore, while CF_3 -CNTPP underwent a two-electron reduction with one drop of $\text{NH}_2\text{NH}_2 \cdot \text{H}_2\text{O}$, it is possible that Zn-CNTPP and Pd-CNTPP only underwent a one-electron reduction with one drop of $\text{NH}_2\text{NH}_2 \cdot \text{H}_2\text{O}$. Furthermore, the difference between the first and second reduction potentials, $E_{\text{red1}} - E_{\text{red2}}$, of Zn-CNTPP and Pd-CNTPP was 0.45 V and 0.46 V in DMSO, respectively. $E_{\text{red1}} - E_{\text{red2}}$ represents the susceptibility of the 19π radical to one-electron reduction; the larger this value, the greater the stability of the 19π radical. The $E_{\text{red1}} - E_{\text{red2}}$ values for Zn-CNTPP and Pd-CNTPP were larger than those for CF_3 -CNTPP (0.27 V). This suggests that the 19π radicals formed by Zn-CNTPP and Pd-CNTPP may be more stable than those of CF_3 -CNTPP. Diazaporphyrins, known as porphyrinoids that form stable 19π radicals, have $E_{\text{red1}} - E_{\text{red2}}$ values of approximately 0.6 V for Zn complexes, Cu complexes, Ni complexes, and the free base.^[20] The values of 0.45 V and 0.46 V for Zn-CNTPP and Pd-CNTPP suggest that the stability of the 19π radical may be lower than that of diazaporphyrins.

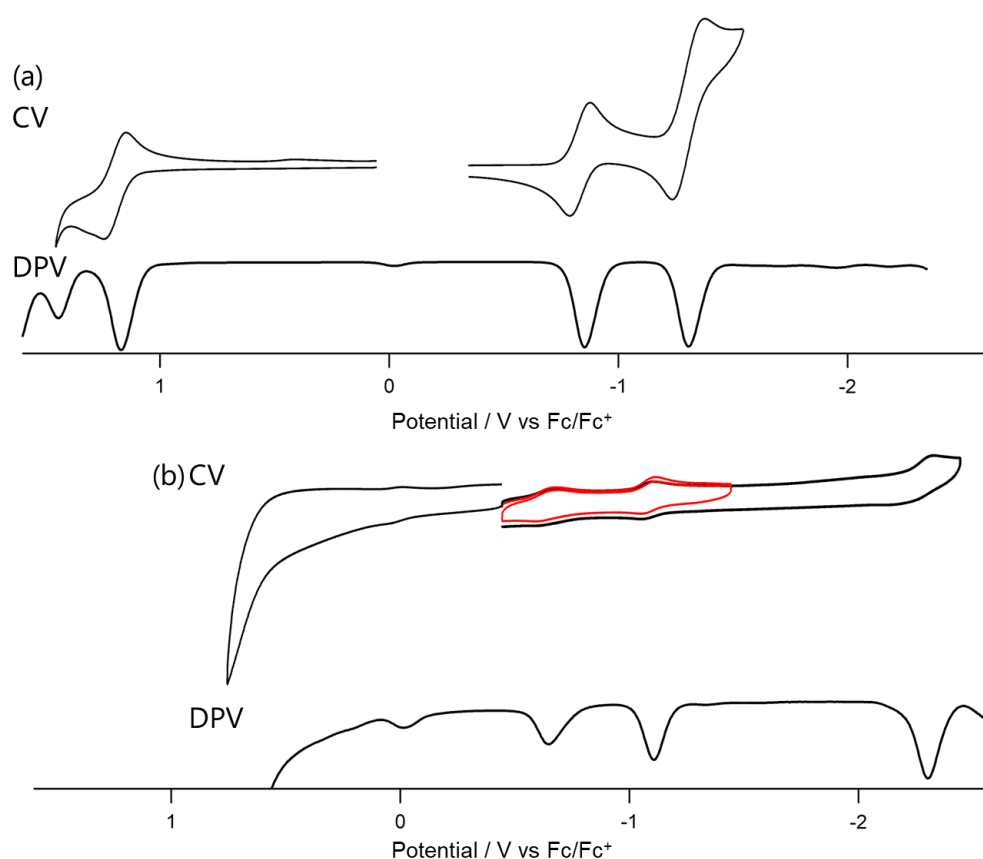


Figure 3.6 Cyclic and differential pulse voltammogram of (a) Pd-CNTPP in CH_2Cl_2 and (b) Pd-CNTPP in DMSO.

The solvent had a pronounced influence on the UV-Vis/near-infrared (NIR) absorption spectra. In the UV-Vis/NIR absorption spectrum of $\text{SnCl}_2\text{-CNTPP}$ in CH_2Cl_2 , the Soret band was observed at approximately 450 nm, and the Q bands were observed at 600–660 nm (Figure 3.7), which are typical of aromatic porphyrins. In contrast, the UV-Vis/NIR absorption spectrum of $\text{SnCl}_2\text{-CNTPP}$ in DMSO exhibited a new broad absorption band at 800–1000 nm. This behavior was also observed for free bases S_2CNTPP ,^[21] and the broad bands can be attributed to the one-electron reduced anion radical of $\text{SnCl}_2\text{-CNTPP}$.

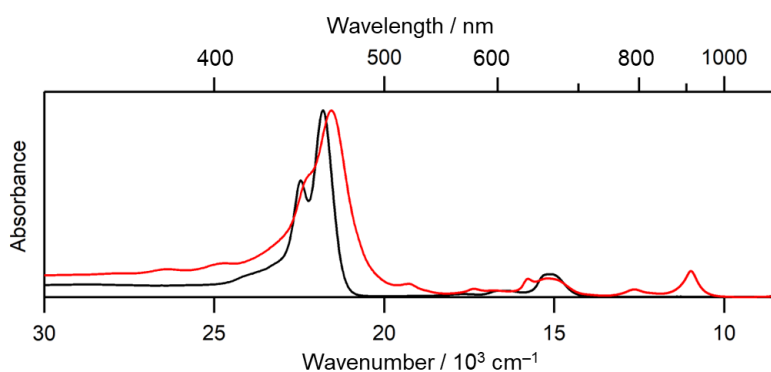


Figure 3.7 UV-Vis/NIR absorption spectra of $\text{SnCl}_2\text{-CNTPP}$ in CH_2Cl_2 (black) and in DMSO (red).

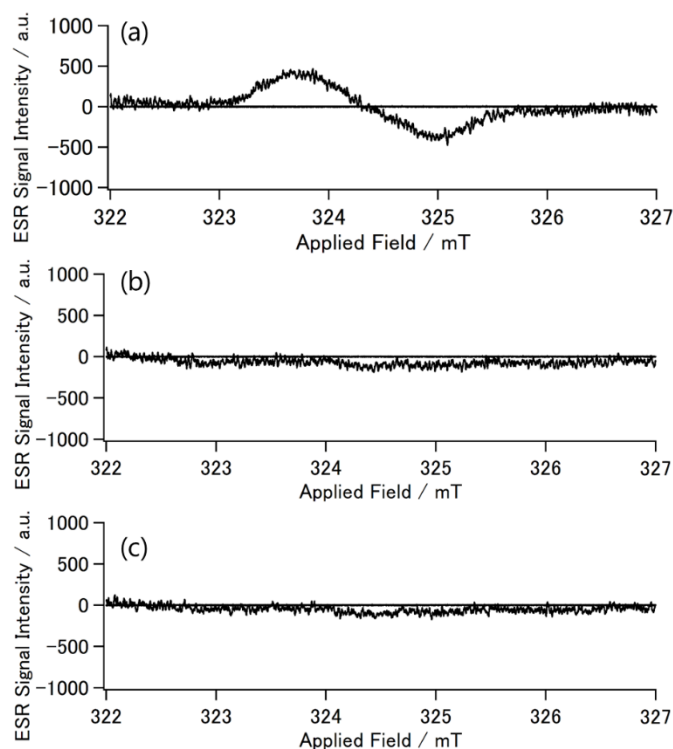


Figure 3.8 ESR spectra of (a) $\text{SnCl}_2\text{-CNTPP}$ in DMSO, (b) $\text{SnCl}_2\text{-CNTPP}$ in DMSO + 1 drop of $\text{NH}_2\text{NH}_2\cdot\text{H}_2\text{O}$ and (c) CNTPP in DMSO.

The generation of anion radical species was also supported by electron spin resonance (ESR) measurements. The ESR spectrum of $\text{SnCl}_2\text{-CNTPP}$ in DMSO showed a signal at $g = 2.00191$, supporting the generation of an anion radical (Figure 3.8). In contrast, no ESR signal was observed for ligand CNTPP in DMSO. These results are due to the higher first reduction potential of $\text{SnCl}_2\text{-CNTPP}$ than of CNTPP.

3.2.2 UV-vis/NIR Absorption Spectra in the Reduction

When $\text{SnCl}_2\text{-CNTPP}$ was reduced with $\text{NH}_2\text{NH}_2 \cdot \text{H}_2\text{O}$ in DMSO, the UV-Vis/NIR spectrum revealed two sharp absorption bands at approximately 450 and 600 nm and a broad weak band at 800–1200 nm are observed (Figure 3.9), which are similar those of $[\text{S}_2\text{CNIph}]^{2-}$, and $[\text{CF}_3\text{-CNIph}]^{2-}$ recorded under the same conditions.^[1,21] This spectral similarity indicates that the two-electron reduction of $\text{SnCl}_2\text{-CNTPP}$ occurs on the ligand rather than on the metal center, affording $\text{SnL}_2\text{-CNIph}$ (L: axial ligand). Time-dependent density functional theory (TDDFT) calculations suggested that these absorption bands can be assigned to $\text{S}_0 \rightarrow \text{S}_1$ (HOMO $\rightarrow$ LUMO), $\text{S}_0 \rightarrow \text{S}_2$ (HOMO $\rightarrow$ LUMO+1), and $\text{S}_0 \rightarrow \text{S}_3$ (HOMO-1 $\rightarrow$ LUMO) transitions (Figure 3.10). For $[\text{S}_2\text{CNIph}]^{2-}$, and $[\text{CF}_3\text{-CNIph}]^{2-}$, weak absorption bands arising from the $\text{S}_0 \rightarrow \text{S}_1$ (HOMO $\rightarrow$ LUMO) transition were observed around 1000 nm,^[1,21] whereas $\text{SnL}_2\text{-CNIph}$ exhibited an absorption band that was more long-wavelength shifted, extending 1200 nm. This suggests that the HOMO–LUMO gap of $\text{SnL}_2\text{-CNIph}$ is smaller than those of $[\text{S}_2\text{CNIph}]^{2-}$, $[\text{CF}_3\text{-CNIph}]^{2-}$, and $[\text{CNIph}]^{2-}$.

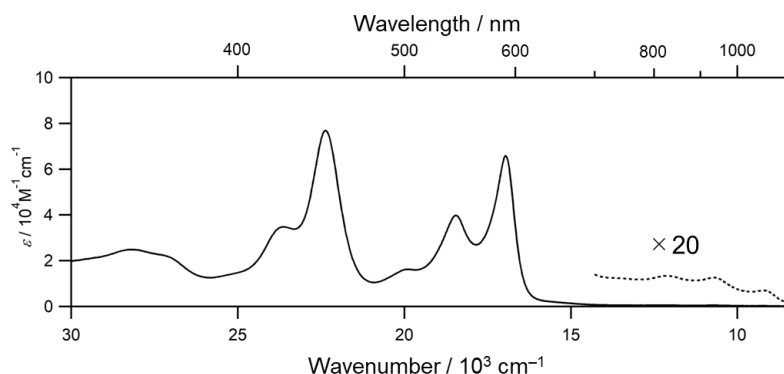


Figure 3.9 UV-Vis/NIR absorption spectrum of $\text{SnCl}_2\text{-CNTPP}$ in DMSO in the presence of $\text{NH}_2\text{NH}_2 \cdot \text{H}_2\text{O}$ (1 %). The dashed line is magnified 20 times.

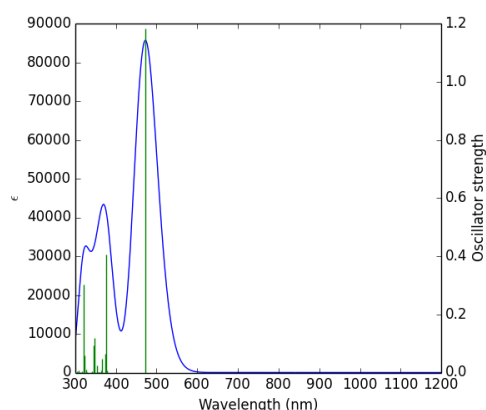


Figure 3.10. Calculated (TDDFT) UV/vis/NIR absorption spectrum of $[\text{Sn}(\text{OMe})_2\text{-CNIph}]^{2-}$.

When a drop of $\text{NH}_2\text{NH}_2 \cdot \text{H}_2\text{O}$ was added to DMSO as a reducing agent, the color of the solution of Zn-CNTPP and Pd-CNTPP remained unchanged. However, a broad absorption band was observed from 700 to 1100 nm in the absorption spectrum (Figure 3.11). This broad absorption band is similar to the absorption band observed in a previous study when S_2CNTPP was dissolved in DMSO.^[21] ESR measurements confirmed that S_2CNTPP was reduced by one electron in DMSO, generating the 19π radical (Scheme 3.1). It has also been reported that the 19π radical diazaporphyrin has a broad absorption band around 900 nm in UV-vis/NIR absorption spectroscopy.^[20] Therefore, it is thought that Zn-CNTPP and Pd-CNTPP were reduced by one electron to generate the 19π radical when a drop of $\text{NH}_2\text{NH}_2 \cdot \text{H}_2\text{O}$ was added as a reducing agent in DMSO solvent.

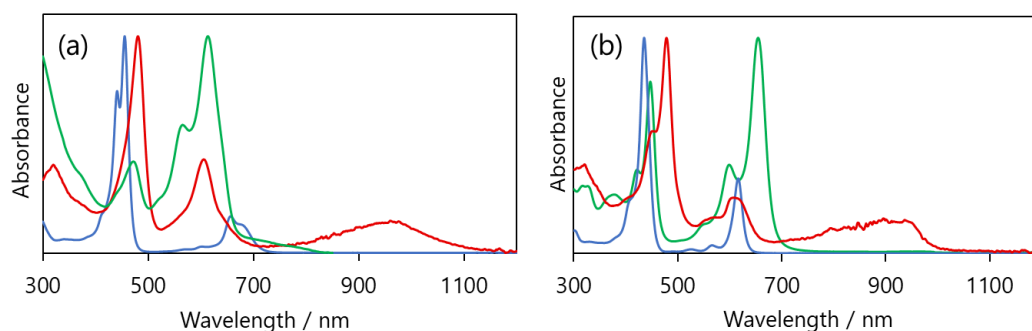
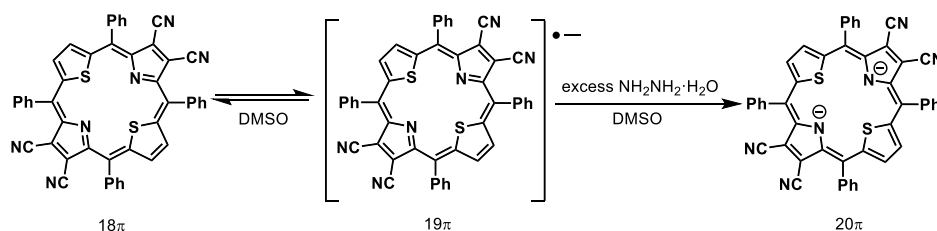


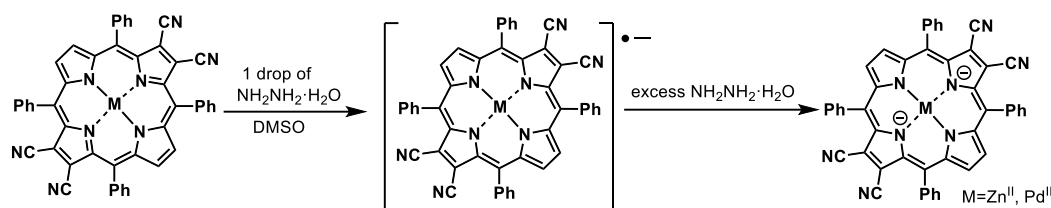
Figure 3.11 UV-vis/NIR absorption spectra of (a) Zn-CNTPP and (b) Pd-CNTPP in CH_2Cl_2 (blue), in DMSO and 1 drop of $\text{NH}_2\text{NH}_2 \cdot \text{H}_2\text{O}$ (red), in $\text{NH}_2\text{NH}_2 \cdot \text{H}_2\text{O}$ (green).

Scheme 3.1 Stepwise reduction of S_2CNTPP .



As in the reduction of CNTPP shown in Chapter 2, when a solvent amount of $\text{NH}_2\text{NH}_2 \cdot \text{H}_2\text{O}$ was used, the absorption spectrum of Zn-CNTPP and Pd-CNTPP changed significantly, matching the waveform after two-electron reduction. However, the solution color of Zn-CNTPP and Pd-CNTPP in $\text{NH}_2\text{NH}_2 \cdot \text{H}_2\text{O}$ was blue, which differed from the red color of $[\text{CNIph}]^{2-}$ in $\text{NH}_2\text{NH}_2 \cdot \text{H}_2\text{O}$. In summary, Zn-CNTPP and Pd-CNTPP exhibited the reduction behavior shown in Scheme 3.2.

Scheme 3.2 Stepwise reduction of Zn-CNTPP and Pd-CNTPP.



3.2.3 ^1H NMR Study in the Reduction to Synthesize Isophlorins

The reduction of SnCl_2 -CNTPP was performed as described for the reduction of S_2CNTPP and CF_3 -CNTPP to obtain the corresponding isophlorin.^[1,21] Treatment of SnCl_2 -CNTPP with hydrazine monohydrate in DMSO resulted in a rapid color change from yellow to reddish-purple. The ^1H NMR spectrum of SnCl_2 -CNTPP reduced with $\text{NH}_2\text{NH}_2 \cdot \text{H}_2\text{O}$ in $[\text{D}_6]\text{DMSO}$ indicated the formation of antiaromatic isophlorin $\text{SnL}_2\text{-CNIph}$ as the sole product (Figure 3.3b). A signal for the β -protons was observed at $\delta = 3.8$ ppm as a singlet with Sn satellite peaks ($^4J_{\text{H-Sn}} = 14.5$ Hz), which was significantly upfield shifted compared to that of SnCl_2 -CNTPP, suggesting a switch from an aromatic to an antiaromatic environment. The chemical shift was more upfield shifted compared to the reported free bases $[\text{S}_2\text{CNIph}]^{2-}$, $[\text{CF}_3\text{-CNIph}]^{2-}$, and $[\text{CNIph}]^{2-}$ (5.0–5.2 ppm),^[1,21] which indicated that the complexation of the Sn(IV) ion enhanced the antiaromaticity in $\text{SnL}_2\text{-CNIph}$. However, compared to the corresponding chemical shifts of previously reported Ge(IV)^[9] and Si(IV)^[7] isophlorins without cyano groups (0.6 and 1.3 ppm, respectively), this chemical shift was more downfield shifted. This suggests that the antiaromaticity of $\text{SnL}_2\text{-CNIph}$ is weaker than that of those Ge and Si isophlorins. This difference is likely not due to the change in metal, but rather, as previously discussed,^[1,21] the electronic perturbation of the isophlorin macrocycle by π -conjugation with the cyano groups, which reduces the antiaromaticity. The obtained isophlorin $\text{SnL}_2\text{-CNIph}$ was stable in the presence of hydrazine even under the air like $[\text{S}_2\text{CNIph}]^{2-}$ and $[\text{CF}_3\text{-CNIph}]^{2-}$.

From the NMR analyses, the axial ligands L of $\text{SnL}_2\text{-CNIph}$ cannot be determined in solution; possible candidates are solvated molecules (DMSO, H_2O , and NH_2NH_2) and OH or Cl anions. Therefore, ESI-HRMS measurements were performed to determine the axial ligands. Because DMSO is generally unsuitable as a solvent for ESI-MS measurements, diluted DMSO solution of $\text{SnL}_2\text{-CNIph}$

with a large excess of methanol prior to measurement was used. The primary ion peaks observed in the resulting spectrum were attributed to species in which the axial ligands had been substituted with methoxy groups, i.e. $[\text{Sn}(\text{OMe})_2\text{-CNiPh}]^{2-}$ (Figure 3.12). This substitution is likely due to the high affinity of Sn ions for oxygen-based anions.^[22] Notably, no clear ion peaks was observed for samples in the other solvents.

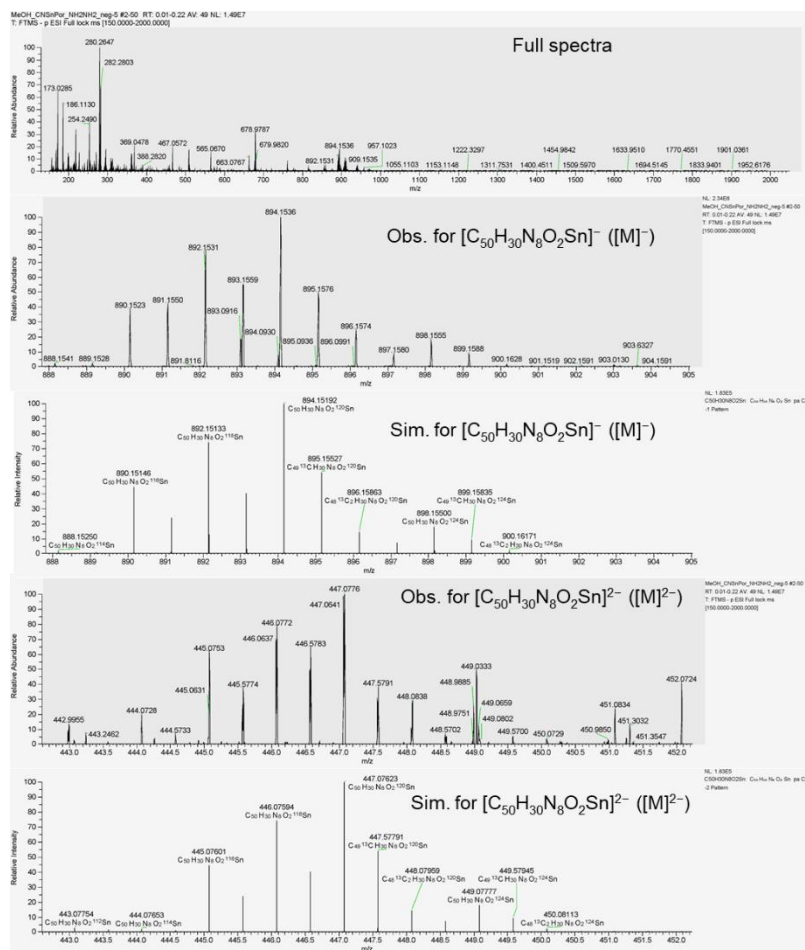


Figure 3.12 ESI-HRMS spectra of $[\text{Sn}(\text{OMe})_2\text{-CNiPh}]^{2-}$ in MeOH.

On the other hand, for Zn-CNTPP and Pd-CNTPP, in measurements before reduction in deuterated chloroform, the β -position protons were observed at 8.7 ppm, respectively (Figure 3.13a and Figure 3.14a). When a drop of $\text{NH}_2\text{NH}_2 \cdot \text{H}_2\text{O}$ was added to deuterated DMSO, most of the signals disappeared and the spectrum became more complex (Figure 3.13b and Figure 3.14b). This is similar to the behavior of CNTPP shown in Chapter 2, Figure 2.4 and is thought to be the result of the one-electron reduction shown in Scheme 3.2, which resulted in the generation of radicals. When measurements were performed using a solvent amount of $\text{NH}_2\text{NH}_2 \cdot \text{H}_2\text{O}$, no significant peaks were observed due to the low solubility of both Zn-CNTPP and Pd-CNTPP.

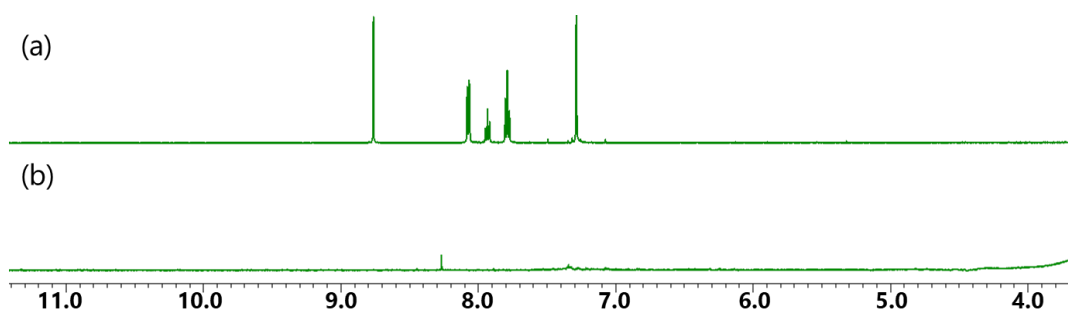


Figure 3.13 ^1H NMR spectra showing the reduction of Zn-CNTPP (500 MHz). (a) Zn-CNTPP in CDCl_3 and 1 drop of $[\text{D}_4]\text{MeOH}$. (b) Zn-CNTPP in situ reduction by the addition of 1 drop of $\text{NH}_2\text{NH}_2 \cdot \text{H}_2\text{O}$ in $[\text{D}_6]\text{DMSO}$.

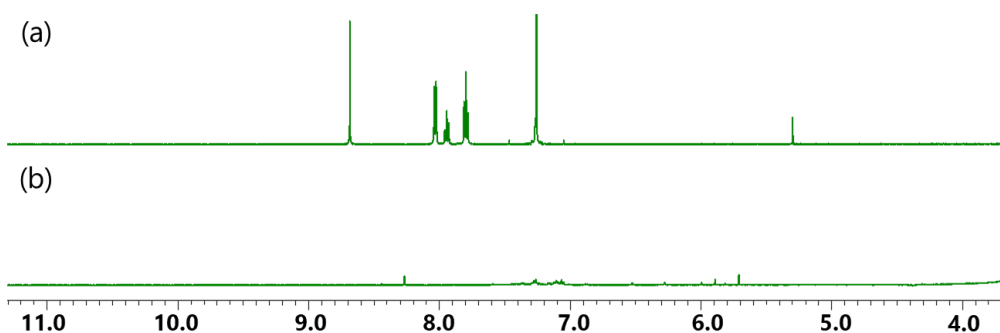


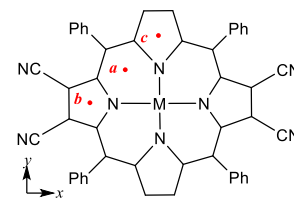
Figure 3.14 ^1H NMR spectra showing the reduction of Pd-CNTPP (500 MHz). (a) Pd-CNTPP in CDCl_3 . (b) Pd-CNTPP in situ reduction by the addition of 1 drop of $\text{NH}_2\text{NH}_2 \cdot \text{H}_2\text{O}$ in $[\text{D}_6]\text{DMSO}$.

3.2.4 Single Crystal Structures

This ligand exchange of $[\text{Sn}(\text{OMe})_2\text{-CNIph}]^{2-}$ was also observed in the X-ray crystal diffraction analysis. The single crystals were only obtained by slow diffusion of tetraphenylphosphonium bromide in methanol into a solution of $\text{SnCl}_2\text{-CNTPP}$ that had been reduced with $\text{NH}_2\text{NH}_2 \cdot \text{H}_2\text{O}$ in DMSO. The X-ray crystal diffraction analysis revealed the molecular structure of $(\text{PPh}_4)_2[\text{Sn}(\text{OMe})_2\text{-CNIph}]$ (Figure 3.15). In the crystal structure, isophlorin had two methoxy ions as the axial ligands and two PPh_4^+ ions were incorporated into the crystal for each molecule, indicating tetravalent Sn ions. The isophlorin macrocycle had high planarity with a small mean plane deviation value of 0.053 Å. This high planarity contrasts sharply with the significant distortion observed in previously reported Ge(IV) and Si(IV) isophlorins without cyano groups.^[7,9] This difference can be attributed to the Sn(IV) ion having an ideal ionic radius for fitting inside the porphyrin ring, as well as the weaker antiaromaticity of $\text{SnL}_2\text{-CNIph}$ compared to the reported Ge(IV) and Si(IV) isophlorins. A more significant bond length alternation was observed compared to that of the porphyrin $\text{SnCl}_2\text{-CNTPP}$ (Figure 3.2), which suggests a loss of aromaticity in $(\text{PPh}_4)_2[\text{Sn}(\text{OMe})_2\text{-CNIph}]$.

Table 3.3 NICS values for $[\text{Sn}(\text{OMe})_2\text{-CNIph}]^{2-}$, $[\text{Zn-CNIph}]^{2-}$, $[\text{Pd-CNIph}]^{2-}$, and $[\text{CNTPP}]^{2-}$.^[a]
Calculated at cam-B3LYP/6-311g(d,p)/LAN2DZ//cam-B3LYP/6-311+G(2d,p)/SDD

	<i>a</i>	<i>b</i>	<i>c</i>
$[\text{Sn}(\text{OMe})_2\text{-CNIph}]^{2-}$	9 (50)	-6 (16)	0 (25)
$[\text{Zn-CNIph}]^{2-}$	8 (47)	-6 (13)	-1 (24)
$[\text{Pd-CNIph}]^{2-}$	6 (43)	-5 (6)	1 (23)
$[\text{CNIph}]^{2-}$	4 (34)	-8 (2)	0 (24)



[a] NICS_{iso} values are shown. NICS_{zz} values are given in parentheses.

The mean plane deviation (MPD) values of the geometry-optimized structures of $[\text{Sn}(\text{OMe})_2\text{-CNIph}]^{2-}$ and $[\text{CNIph}]^{2-}$ were 0.177 Å and 0.471 Å, respectively (Figure 3.17). The significant difference in planarity suggests that coordination of the Sn(IV) ion likely enhances the planarity of isophlorin, which, in turn, leads to the observed increase in antiaromaticity. Notably, while the geometry-optimized structure of $[\text{Sn}(\text{OMe})_2\text{-CNIph}]^{2-}$ closely matches its crystal structure, $[\text{CNIph}]^{2-}$ exhibits relatively high planarity in the crystal. This discrepancy between the calculated and crystal structures of $[\text{CNIph}]^{2-}$ may be attributed to crystal packing effects, which are not accounted for in the gas-phase calculations.

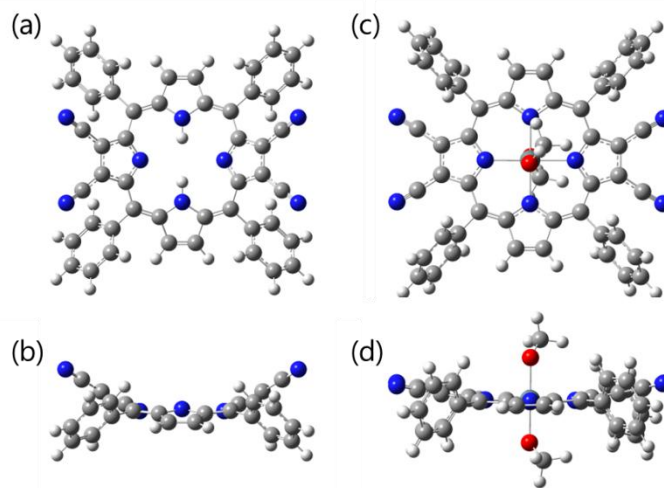


Figure 3.17 Optimized structures of isophlorins. (a) $[\text{CNIph}]^{2-}$ top view, (b) $[\text{CNIph}]^{2-}$ side view, (c) $[\text{Sn}(\text{OMe})_2\text{-CNIph}]^{2-}$ top view, and (d) $[\text{Sn}(\text{OMe})_2\text{-CNIph}]^{2-}$ side view.

The NICS values for $[\text{Zn-CNIph}]^{2-}$ and $[\text{Pd-CNIph}]^{2-}$ were also calculated (Table 3.2). Among the isophlorin metal complexes at point *a*, the Sn complex demonstrated the strongest antiaromaticity, followed by the Zn complex, while the Pd complex exhibited the weakest antiaromaticity. This suggests that modifying the metal ion coordinated to isophlorin allows tuning the strength of antiaromaticity. Future research on substituents of Zn-CNTPP and Pd-CNTPP to enhance

reduction potential for chemical reduction is expected to provide detailed insights into the antiaromaticity of isophlorin metal complexes.

3.3 Summary

In this chapter, β -tetracyanoporphyrin metal complexes with metal centered Zn(II), Pd(II), and Sn(IV) were synthesized, and attempted to reduce the corresponding isophlorin metal complexes. CV measurements were performed to investigate the electrochemical properties of the isophlorin precursor. SnCl_2 -CNTPP exhibited a higher reduction potential than CF_3 -CNTPP, indicating its ease of reduction. This is likely due to the formation of a 1:1 neutral complex between tetravalent Sn and isophlorin, stabilizing the resulting isophlorin. Indeed, SnCl_2 -CNTPP was reduced with a single drop of $\text{NH}_2\text{NH}_2 \cdot \text{H}_2\text{O}$, similar to S_2 CNTPP and CF_3 -CNTPP, to give the two-electron reduced product $\text{SnL}_2\text{-CNIph}$. The central Sn ion enhances the planarity of the isophlorin structure, resulting in stronger antiaromaticity compared to those of the free-base forms $[\text{S}_2\text{CNIph}]^{2-}$ and $[\text{CF}_3\text{-CNIph}]^{2-}$. This enhanced antiaromaticity was confirmed by NMR spectroscopy, X-ray crystallography, and NICS calculations. Importantly, $\text{SnL}_2\text{-CNIph}$ is remarkably stable in air, in contrast to previously reported Si(IV) and Ge(IV) isophlorin complexes without cyano groups. This stability, combined with the ease of synthesis using mild reducing agents, makes $\text{SnL}_2\text{-CNIph}$ an attractive candidate for further studies and applications. On the other hand, Zn-CNTPP and Pd-CNTPP exhibited lower reduction potentials than SnCl_2 -CNTPP, CNTPP, and CF_3 -CNTPP. Notably, compared with CF_3 -CNTPP, the first reduction potentials of Zn-CNTPP and Pd-CNTPP were comparable to the second reduction potential of CF_3 -CNTPP, suggesting that only one-electron reduction will proceed with a single drop of $\text{NH}_2\text{NH}_2 \cdot \text{H}_2\text{O}$. UV-vis/NIR absorption spectra of Zn-CNTPP and Pd-CNTPP suggested that they were reduced with a single drop of $\text{NH}_2\text{NH}_2 \cdot \text{H}_2\text{O}$ to produce the 19π radical. Using $\text{NH}_2\text{NH}_2 \cdot \text{H}_2\text{O}$ as solvent, absorption spectra consistent with the two-electron reduction product were obtained, but ^1H NMR data were not obtained due to the low solubility. To conclude, the reduction behavior of Zn-CNTPP and Pd-CNTPP, and SnCl_2 -CNTPP differ depending on the central metal, and changing the central metal can change the properties of isophlorin and precursor porphyrin.

3.4 Experimental Section

3.4.1 Instrumental and Chemicals

All instruments and chemicals are as described in Chapter 2.4.1.

3.4.2 Synthetic Procedures

Bischloride[7,8,17,18-tetracyano-5,10,15,20-tetraphenyl]porphyrinato]tin(IV) (SnCl_2 -CNTPP)

This compound was synthesized in a similar manner to the synthesis of the related compounds.^[16] To

a solution of CNTPP (185 mg, 0.259 mmol) in pyridine (74 mL), tin(II) dichloride dihydride (158 mg, 0.701 mmol) was added. The resultant solution was refluxed for 16 h. After cooling to room temperature, excess hexane was added to the resulting solution to precipitate the product, which was then collected by filtration. The obtained precipitate was a mixture of the desired product and compounds where the axial ligands had been exchanged with OH. Therefore, the precipitate was dissolved in CHCl_3 and washed with 1 M HCl aq. ($\times 1$), water ($\times 1$), NaHCO_3 aq. ($\times 1$) and brine ($\times 1$) and dried over Na_2SO_4 . Solvent was removed under reduced pressure. Recrystallization from CHCl_3 /hexane gave SnCl_2 -CNTPP as a purple solid (224 mg, 0.249 mmol, 96%). M.p. $>300^\circ\text{C}$; ^1H NMR (500 MHz, CDCl_3): δ = 9.10 (s, 4H; PorH_b), 8.19 (d, J = 6.9 Hz, 8H; PhH_o), 8.04 (t, J = 7.8 Hz, 4H; PhH_p), 7.89 ppm (t, J = 7.8 Hz, 8H; PhH_m); ^{13}C NMR (125 MHz, CDCl_3): δ = 149.5 (Cq), 141.8 (Cq), 137.1 (Cq), 135.6 (CH), 134.3 (CH), 131.3 (CH), 128.1 (CH), 123.7 (Cq), 123.3 (Cq), 110.6 ppm (Cq); UV/vis (CH_2Cl_2): λ_{max} (Log ϵ) = 446 (5.28), 459 (5.49), 566 (3.64), 602 (3.99), 663 nm (4.56); HRMS(ESI): m/z : calcd for $\text{C}_{48}\text{H}_{24}\text{N}_8\text{SnCl}_2$: 902.0528 $[\text{M}]^-$; found: 902.0533; elemental analysis calcd (%) for $\text{C}_{48}\text{H}_{24}\text{N}_8\text{SnCl}_2 \cdot 0.5\text{H}_2\text{O}$: C 63.26, H 2.76, N 12.29; found: C 63.26, H 2.82, N 12.18.

Reduction of SnCl_2 -CNTPP and isolation of $[\text{SnL}_2\text{-CNIph}]^{2-}$

To a solution of SnCl_2 -CNTPP in DMSO (or $[\text{D}_6]\text{DMSO}$), a few drops of $\text{NH}_2\text{NH}_2 \cdot \text{H}_2\text{O}$ were added until the color of the solution changed rapidly to reddish-purple. ^1H NMR and UV-vis/NIR analyses revealed the quantitative formation of $[\text{SnL}_2\text{-CNIph}]^{2-}$. ^1H NMR (500 MHz, $[\text{D}_6]\text{DMSO} + 1\%$ $\text{NH}_2\text{NH}_2 \cdot \text{H}_2\text{O}$, 40°C): δ = 7.08 (t, J = 7.7 Hz, 8H; PhH_m), 7.00 (t, J = 7.2 Hz, 4H; PhH_p), 6.58 (d, J = 7.4 Hz, 8H; PhH_o), 3.78 ppm (s, 4H; IphH_b); ^{13}C NMR (125 MHz, $[\text{D}_6]\text{DMSO} + 1\%$ $\text{NH}_2\text{NH}_2 \cdot \text{H}_2\text{O}$): δ = 154.9 (Cq), 154.0 (Cq), 136.5 (Cq), 131.0 (CH), 129.3 (CH), 128.7 (CH), 127.5 (CH), 112.3 (Cq), 109.0 (Cq), 95.6 ppm (Cq); UV-Vis/NIR (DMSO + 1% $\text{NH}_2\text{NH}_2 \cdot \text{H}_2\text{O}$): λ_{max} (Log ϵ) = 355 (4.40), 423 (4.54), 447 (4.89), 503 (4.21), 542 (4.60), 590 (4.82), 825 (2.83), 935 (2.80), 1085 nm (2.54).

[7,8,17,18-Tetracyano-5,10,15,20-tetraphenylporphyrinato]zinc(II) (Zn-CNTPP)

CNTPP (43 mg, 0.060 mmol) and zinc acetate (259 mg, 1.18 mmol) were dissolved in 2 mL of $\text{CHCl}_3/\text{MeOH}$ (10:1 v/v). The resultant solution was heated at 55°C for 16 h. After cooling to room temperature, the resultant solution was passed through a pat of almina column and eluted with CHCl_3 , and then concentrated under the reduced pressure. Recrystallization from CHCl_3 /hexane gave Zn-CNTPP as a purple solid (37 mg, 0.047 mmol, 79%). ^1H NMR (400 MHz, CDCl_3 and a drop of $[\text{D}_1]\text{MeOH}$): δ = 8.72 (s, 4H; PorH_b), 8.04 (d, $^3J_{\text{H-H}}$ = 7.25 Hz, 8H; PhH_o), 7.87 (t, $^3J_{\text{H-H}}$ = 6.87 Hz, 4H; PhH_p), 7.73 ppm (t, $^3J_{\text{H-H}}$ = 6.87 Hz, 8H; PhH_m). The NMR spectrum was corresponded with previous report.^[25]

[7,8,17,18-Tetracyano-5,10,15,20-tetraphenylporphyrinato]palladium(II) (Pd-CNTPP)

CNTPP (41 mg, 0.057 mmol) and palladium acetate (55 mg, 0.25 mmol) were dissolved in 2 mL of CHCl₃/MeOH (10:1 v/v). The resultant solution was heated at 55 °C for 16 h. After cooling to room temperature, the resultant solution was passed through a pat of silica gel column and eluted with CHCl₃, and then concentrated under the reduced pressure. The crude product was purified by column chromatography (silica gel, CH₂Cl₂). Recrystallization from CHCl₃/MeOH gave Pd-CNTPP as a green solid (35 mg, 0.043 mmol, 75%). M.p. >300 °C; ¹H NMR (500 MHz, CDCl₃): δ = 8.69 (s, 4H; PorH_b), 8.03 (d, ³J_{H-H} = 8.13 Hz, 8H; PhH_o), 7.94 (t, ³J_{H-H} = 7.65 Hz, 4H; PhH_p), 7.98 ppm (t, ³J_{H-H} = 7.65 Hz, 8H; PhH_m); ¹³C NMR (125 MHz, CDCl₃): δ = 145.6 (Cq), 137.9 (Cq), 137.8 (Cq), 134.3 (CH), 133.8 (CH), 130.6 (CH), 127.8 (CH), 124.3 (Cq), 121.2 (Cq), 111.3 ppm (Cq); HRMS(ESI): *m/z*: calcd for C₄₈H₂₄N₈Pd: 818.1164 [*M*]⁺; found: 818.1180.

3.4.3 NMR Spectra of New Compounds

Bischloride[7,8,17,18-tetracyano-5,10,15,20-tetraphenyl)porphyrinato]tin(IV) (SnCl₂-CNTPP)

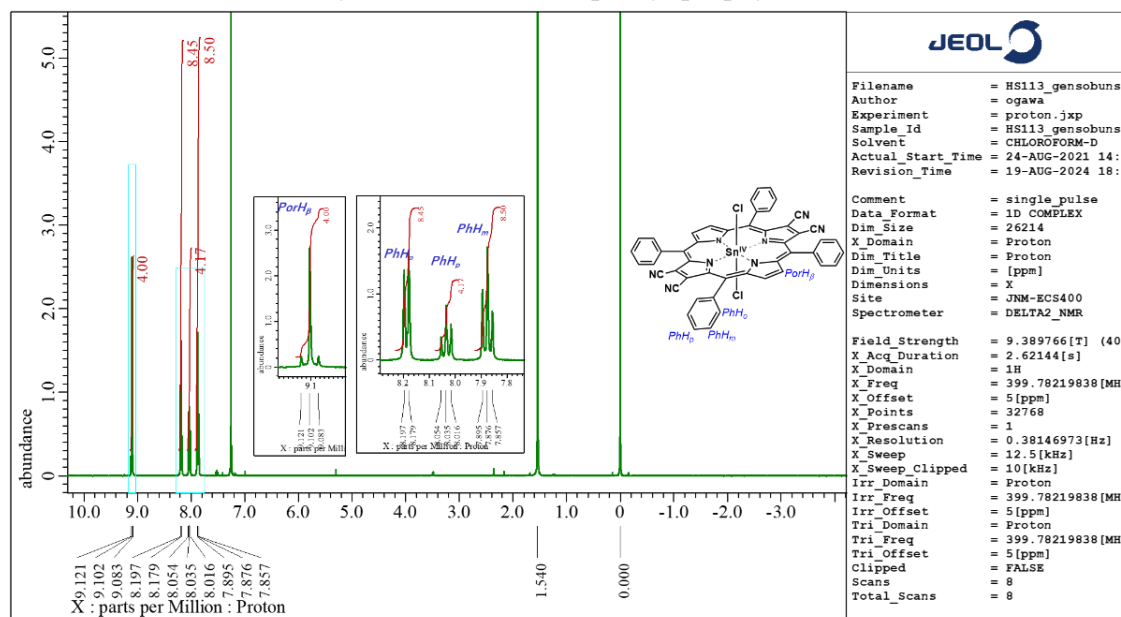


Figure E3.1 ¹H NMR spectrum in CDCl₃.

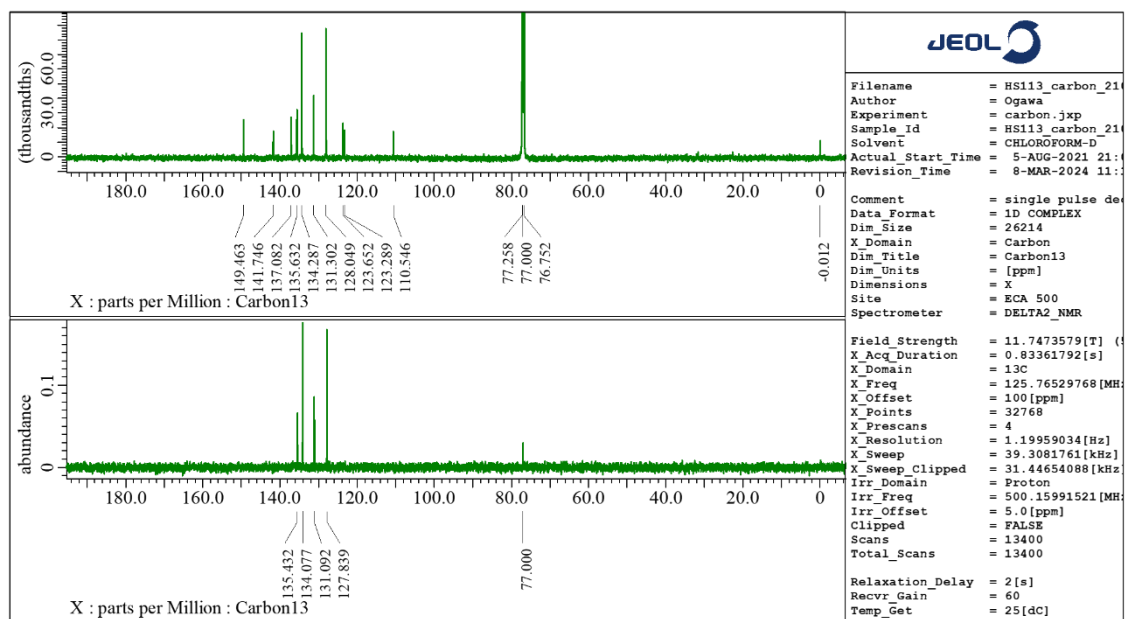


Figure E3.2 ^{13}C NMR spectra (above) and dept135 (down) in CDCl_3 .

SnL₂-CNIph

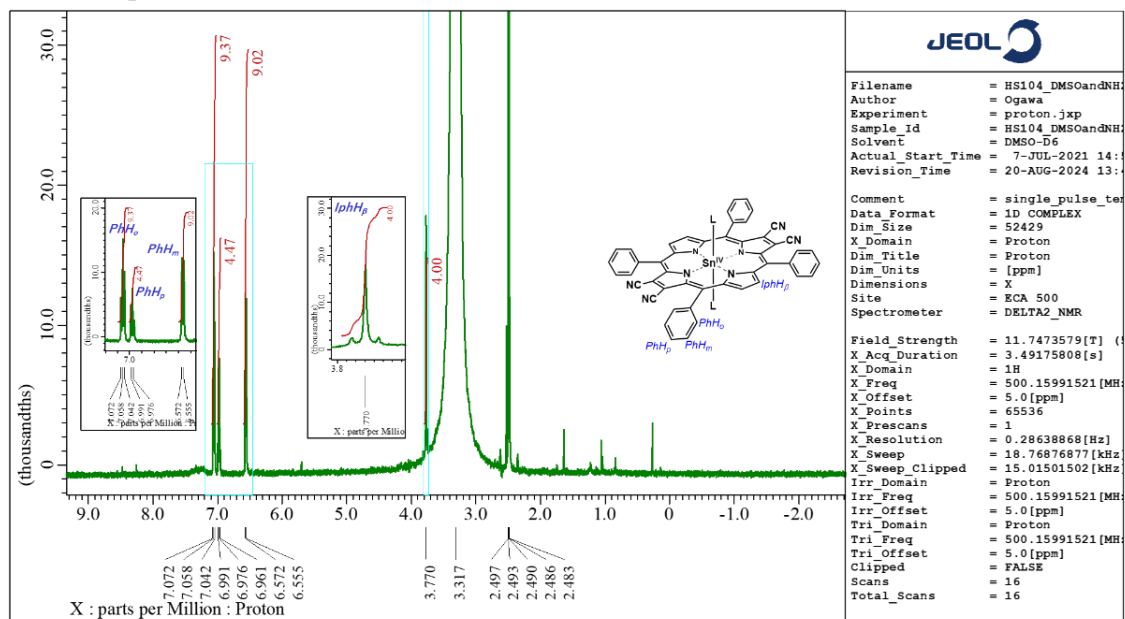


Figure E3.3 ^1H NMR spectrum in $[\text{D}_6]\text{DMSO}$.

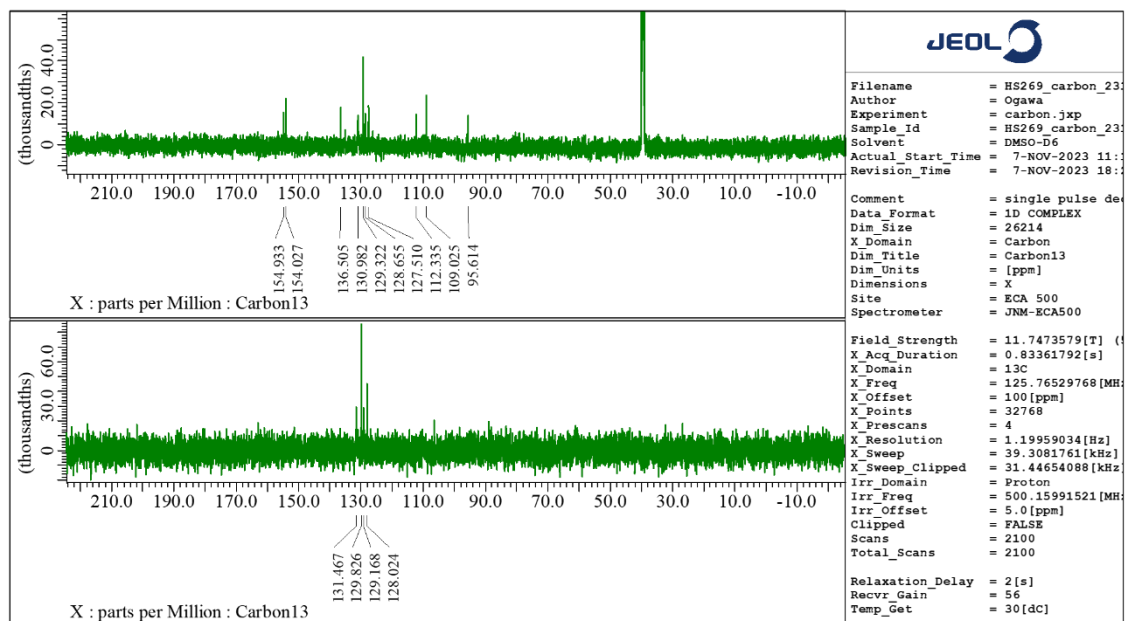


Figure E3.4 ^{13}C NMR (above) and dept135 (down) spectra in $[\text{D}_6]\text{DMSO}$.

3.4.4 X-ray Crystal Structure Determinations

All techniques and software are as described in Chapter 2.4.4. The crystallographic data is summarized in Table E3.1. Deposition Numbers 2385350 (for $\text{SnCl}_2\text{-CNTPP}$) and 2385351 (for $(\text{PPh}_4)_2[\text{Sn}(\text{OMe})_2\text{-CNIph}]$) contain the supplementary crystallographic data for these crystals. Single crystals of $\text{SnCl}_2\text{-CNTPP}$ suitable for X-ray diffraction study were obtained by slow diffusion of cyclohexane into a solution of $\text{SnCl}_2\text{-CNTPP}$ in THF, while those of $(\text{PPh}_4)_2[\text{Sn}(\text{OMe})_2\text{-CNIph}]$ were obtained by slow diffusion of tetraphenylphosphonium bromide in methanol into a solution of $\text{SnCl}_2\text{-CNTPP}$ (just reduced by $\text{NH}_2\text{NH}_2 \cdot \text{H}_2\text{O}$) in DMSO.

3.4.5 DFT Calculations

All calculations were carried out as described in Chapter 2.4.5. The coordinates of the optimized structure can be found in the supporting information of the foundational papers. Geometries of all models were optimized by the DFT method at the cam-B3LYP level. Stuttgart RSC 1997 ECP and the associated basis set (SDD)^[26] were used for the Sn atom and the 6-311+G(d,p) basis set was used for the other light atoms. For the coordinates of the optimized structure, see pp. S11–S19 (in https://aces.onlinelibrary.wiley.com/action/downloadSupplement?doi=10.1002%2Fajoc.202400550&file=ajoc202400550-sup-0001-misc_information.pdf). Frequency calculations were performed to confirm that the optimized geometries were not in the saddle points but stable points. Nucleus-independent chemical shifts (NICS) values were calculated at the GIAO-cam-B3LYP/6-311+G(2d,p),SDD(for Sn) level.

Table E3.1 Crystallographic data.

	SnCl ₂ -CNTPP·2cyclohexane	(PPh ₄) ₂ [Sn(OMe) ₂ - CNlph]·2MeOH
CCDC No.	2385350	2385351
empirical formula	C ₆₆ H ₆₀ Cl ₂ N ₈ Sn	C ₁₀₀ H ₇₈ N ₈ O ₄ P ₂ Sn
formula weight	1154.81	1636.33
temperature / K	153	123
crystal system	Monoclinic	Monoclinic
space group	P2 ₁ /n	P2 ₁ /c
<i>a</i> / Å	13.0141(6)	10.6205(3)
<i>b</i> / Å	10.0514(4)	12.7464(4)
<i>c</i> / Å	20.7463(12)	29.8650(14)
<i>a</i> / deg	90	90
<i>b</i> / deg	98.609(5)	98.482(3)
<i>g</i> / deg	90	90
<i>V</i> / Å ³	2683.2(2)	3998.7(3)
<i>Z</i>	2	2
<i>D</i> (calcd) / g cm ⁻³	1.429	1.359
<i>m</i> / mm ⁻¹	0.628	0.421
<i>F</i> (000)	1192	1692
crystal size / mm ³	0.20 × 0.15 × 0.04	0.38 × 0.08 × 0.02
<i>q</i> range for data collection / deg	1.738 to 30.516	1.740 to 30.783
index ranges	−17 ≤ <i>h</i> ≤ 16, −10 ≤ <i>k</i> ≤ 13, −25 ≤ <i>l</i> ≤ 27	−14 ≤ <i>h</i> ≤ 14, −16 ≤ <i>k</i> ≤ 18, −41 ≤ <i>l</i> ≤ 37
reflections collected	31287	45031
independent reflections	6840 [R(int) = 0.0558]	10425 [R(int) = 0.0539]
completeness	100.0%	99.3%
data / restraints / parameters	6840 / 372 / 404	10425 / 0 / 524
GOF on <i>F</i> ²	1.017	1.057
final <i>R</i> indices [<i>I</i> > 2σ(<i>I</i>)] ^a	<i>R</i> ₁ = 0.0485, <i>wR</i> ₂ = 0.1233	<i>R</i> ₁ = 0.0343, <i>wR</i> ₂ = 0.0781
<i>R</i> indices (all data) ^a	<i>R</i> ₁ = 0.0787, <i>wR</i> ₂ = 0.1426	<i>R</i> ₁ = 0.0528, <i>wR</i> ₂ = 0.0837
largest diff. peak and hole / e·Å ⁻³	0.960 and −0.851	0.882 and −1.133

^a *R*₁ = Σ||*F*_o|| − |*F*_c| / Σ|*F*_o|, *wR*₂ = [Σ[*w*(*F*_o² − *F*_c²)²] / Σ*w*(*F*_o²)²]^{1/2}.

Table E3.2 Summary of the TDDFT calculation of [Sn(OMe)₂-CNIph]²⁻.

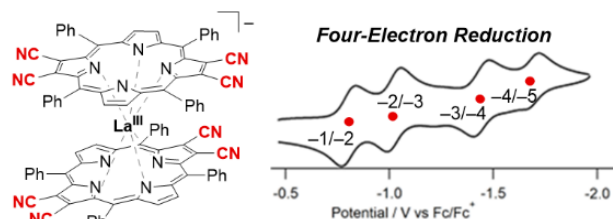
No.	Energy (cm ⁻¹)	Wavelength (nm)	Osc. Strength	Major contribution
1	11925.71	838.5242	0.0001	HOMO->LUMO (96%)
2	21151.08	472.789	1.1823	HOMO->L+1 (98%)
3	26488.05	377.5287	0.0073	HOMO->L+2 (51%), HOMO->L+7 (27%)
4	26626.78	375.5617	0.4049	H-1->LUMO (81%)
5	26650.98	375.2208	0.0643	HOMO->L+3 (34%), HOMO->L+6 (31%)
6	27330.9	365.8862	0.0468	HOMO->L+2 (23%), HOMO->L+7 (23%)
7	27511.57	363.4834	0.0073	HOMO->L+10 (46%), HOMO->L+11 (20%)
8	27714.02	360.8282	0.0006	HOMO->L+12 (17%), HOMO->L+13 (60%)
9	27958.4	357.6742	0.0017	HOMO->L+3 (45%), HOMO->L+6 (16%)
10	28049.54	356.512	0.0003	HOMO->L+4 (69%), HOMO->L+5 (14%)
11	28327	353.0201	0.0239	HOMO->L+5 (61%), HOMO->L+15 (16%)
12	28828.67	346.8769	0.1181	HOMO->L+14 (45%), HOMO->L+17 (26%)
13	28966.6	345.2252	0.0928	HOMO->L+5 (15%), HOMO->L+15 (59%)
14	29221.47	342.2142	0.0047	HOMO->L+16 (87%)
15	29305.35	341.2346	0.0012	HOMO->L+18 (66%)
16	30399.84	328.9491	0.0002	H-1->L+1 (90%)
17	30528.09	327.5672	0.0092	HOMO->L+8 (62%)
18	31036.21	322.2042	0.0587	H-2->LUMO (14%), HOMO->L+9 (21%)
19	31137.84	321.1527	0.3026	H-2->LUMO (79%)
20	31529.02	317.1681	0.0037	HOMO->L+6 (11%), HOMO->L+17 (27%)
21	32021.02	312.2949	0.0002	HOMO->L+10 (21%), HOMO->L+11 (37%)
22	32324.28	309.365	0.0085	H-3->LUMO (30%), HOMO->L+26 (39%)
23	32698.52	305.8242	0.0021	HOMO->L+12 (50%), HOMO->L+13 (15%)
24	32844.51	304.4649	0.0049	H-3->LUMO (60%), HOMO->L+26 (25%)
25	32906.61	303.8903	0.0017	HOMO->L+12 (13%), HOMO->L+19 (42%)
26	33216.33	301.0567	0.002	HOMO->L+19 (11%), HOMO->L+21 (53%)
27	33334.09	299.9932	0.0031	H-4->LUMO (95%)
28	33554.28	298.0246	0.0003	HOMO->L+20 (59%)
29	34189.04	292.4914	0.0023	HOMO->L+23 (61%)
30	34888.32	286.6289	0.0106	HOMO->L+24 (56%)

3.5 References

- [1] H. Sugimura, K. Nakajima, K. Yamashita, T. Ogawa, *Eur. J. Org. Chem.* **2022**, e202200747.
- [2] J. S. Reddy, V. G. Anand, *J. Am. Chem. Soc.* **2008**, *130*, 3718–3719.
- [3] S. P. Panchal, S. C. Gadekar, V. G. Anand, *Angew. Chem. Int. Ed Engl.* **2016**, *55*, 7797–7800.
- [4] S. P. Panchal, S. C. Gadekar, V. G. Anand, *Angew. Chem. Weinheim Bergstr. Ger.* **2016**, *128*, 7928–7931.
- [5] K. M. Kadish, K. M. Smith, R. Guilard, Eds., *The Porphyrin Handbook*, **1999**.
- [6] R. Cosmo, C. Kautz, K. Meerholz, J. Heinze, K. Müllen, *Angew. Chem., Int. Ed. Engl.* **1989**, *28*, 604–607.
- [7] J. A. Cissell, T. P. Vaid, A. L. Rheingold, *J. Am. Chem. Soc.* **2005**, *127*, 12212–12213.
- [8] H.-E. Song, J. A. Cissell, T. P. Vaid, D. Holten, *J. Phys. Chem. B* **2007**, *111*, 2138–2142.
- [9] J. A. Cissell, T. P. Vaid, G. P. A. Yap, *J. Am. Chem. Soc.* **2007**, *129*, 7841–7847.
- [10] D. P. Arnold, J. Blok, *Coord. Chem. Rev.* **2004**, *248*, 299–319.
- [11] B. Babu, J. Mack, T. Nyokong, *Dalton Trans.* **2023**, *52*, 5000–5018.
- [12] J. H. Furhop, K. M. Kadish, D. G. Davis, *J. Am. Chem. Soc.* **1973**, *95*, 5140–5147.
- [13] C. C. Wamser, A. Ghosh, *JACS Au* **2022**, *2*, 1543–1560.
- [14] P. Sayer, M. Gouterman, C. R. Connell, *Acc. Chem. Res.* **1982**, *15*, 73–79.
- [15] A. Ghosh, J. Conradie, *J. Phys. Chem. A* **2021**, *125*, 9962–9968.
- [16] P. Rothmund, A. R. Menotti, *J. Am. Chem. Soc.* **1948**, *70*, 1808–1812.
- [17] D. L. Cullen, E. F. Meyer Jr, *Acta Crystallogr. B* **1973**, *29*, 2507–2515.
- [18] D. P. Arnold, *Polyhedron* **1986**, *5*, 1957–1963.
- [19] X. Ke, R. Kumar, M. Sankar, K. M. Kadish, *Inorg. Chem.* **2018**, *57*, 1490–1503.
- [20] K. Sudoh, K. Furukawa, H. Nakano, S. Shimizu, Y. Matano, *Heteroat. Chem.* **2018**, *29*, e21456.
- [21] K. Yamashita, K. Nakajima, Y. Honda, T. Ogawa, *Chem. Eur. J.* **2020**, *26*, 3633–3640.
- [22] S. J. Webb, J. K. Sanders, *Inorg. Chem.* **2000**, *39*, 5920–5929.
- [23] J. M. Barbe, C. Ratti, P. Richard, C. Lecomte, R. Gerardin, R. Guilard, *Inorg. Chem.* **1990**, *29*, 4126–4130.
- [24] M. R. Maurya, V. Prakash, T. A. Dar, M. Sankar, *ACS Omega* **2023**, *8*, 6391–6401.
- [25] P. Bhyrappa, M. Sankar, B. Varghese, *Inorg. Chem.* **2006**, *45*, 4136–4149.
- [26] M. Dolg, U. Wedig, H. Stoll, H. Preuss, *J. Chem. Phys.* **1987**, *86*, 866–872.

Chapter 4.

Synthesis and Reduction Behavior of the Rare-Earth Double-Decker Complexes Aiming for Stacking Antiaromatic Isophlorin



Abstract: Porphyrin double-decker complexes undergo multiple redox processes that significantly alter their structural and electronic properties, although most studies have focused on oxidation processes. Studies of reduction have remained limited, particularly for porphyrin-based systems in which accessing multiply-reduced states remains challenging. Here the synthesis and characterization of lanthanum(III) porphyrin double-decker complex [La(CNTPP)₂]⁻ was reported, that exhibits unprecedented four-electron reduction capability, reaching the pentaanion state. This work demonstrates a rational design strategy for accessing multiply-reduced porphyrin double-decker complexes and opens new possibilities for applications in molecular electronics and redox-switchable molecular devices.

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4.1 Introduction

Porphyrin double-decker complexes have a sandwich-like structure in which two 18 π aromatic porphyrin ligands coordinate to a metal ion with a large atomic radius, such as a rare-earth ion. These complexes have attracted considerable attention owing to their unique absorption, redox, and magnetic properties, as well as rotational dynamics of the porphyrin ligands.^[1–5]

Trivalent rare-earth porphyrin double-decker complexes with unoxidized porphyrin ligands can be formulated as monoanion species $[M^{III}(\text{por})_2]^-$ or protonated neutral forms $[M^{III}(\text{por})(\text{porH})]$ (Figure 4.1a). This charge state arises from simple charge balance: the rare-earth ion has a formal oxidation state of +3, while each porphyrin dianion ligand contributes -2 , resulting in an overall charge of -1 for the monoanion. In the protonated neutral form, one porphyrin is protonated to give a monoanionic ligand (porH^-), resulting in an overall neutral complex.

In addition to these forms, double-decker complexes can be oxidized to generate two other stable redox states: the neutral radical forms $[M^{III}(\text{por})_2]^0$ and the monocation forms $[M^{III}(\text{por})_2]^+$. Each state displays characteristic absorption spectra and structural features.^[6–10] Among these, the redox properties of double-decker complexes have garnered significant attention for their ability to modulate single-molecule magnet characteristics^[11–16] and nonlinear optics (NLO),^[17,18] and for their potential applications in molecular machines.^[19]

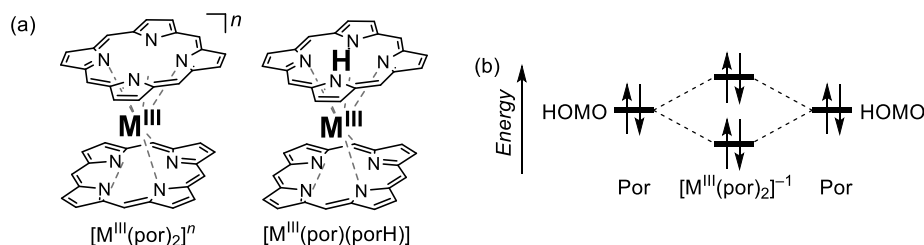


Figure 4.1 Structures and energy diagrams of porphyrin double-decker complexes. (a) Structures of deprotonated form with multiple redox forms (left) and protonated form (right). (b) Two orbitals of the double-decker monoanion species are generated by the HOMO of the ligand. One orbital is stabilized while the other is destabilized due to the interactions of the two porphyrin ligands. “Por” refers to the porphyrin ligand.

The electronic structure of $[M^{III}(\text{por})_2]^-$ explains their facile oxidation behavior (Figure 4.1b).^[6,20] Porphyrin ligands inherently possess high-lying HOMO levels, making them susceptible to oxidation. When two porphyrin ligands form a double-decker complex, their HOMOs interact to generate bonding and antibonding MOs. Two electrons occupy the destabilized antibonding HOMO, further elevating its energy compared to the free ligand. Combined with the negative charge of the monoanion form, these factors make double-decker complexes remarkably easy to oxidize. For example, $[\text{La}(\text{TPP})_2]^-$ (TPP = tetraphenylporphyrinato dianion) shows the first and second oxidation

potential of -0.30 and 0.05 V (vs Fc/Fc⁺) in CH₂Cl₂, respectively.^[6]

In contrast, reduction of these complexes is considerably more difficult. Porphyrin ligands inherently possess relatively high-lying LUMO levels, making them less susceptible to reduction than to oxidation. Although the LUMO–LUMO interaction in the double-decker structure—analogueous to the HOMO–HOMO interaction described above—forms a stabilized bonding orbital that would favor reduction, this effect is outweighed by two other factors: the inherently high LUMO energy of the porphyrin ligand and, more importantly, the electrostatic difficulty of adding electrons to an already negatively charged monoanion species to form multiply-charged anions. Consequently, double-decker complexes exhibit strong resistance to reduction. For example, [La(TPP)₂][–] shows the first reduction potential of -2.06 V (vs Fc/Fc⁺) in DMF,^[6] clearly demonstrating the substantial energy barrier for reduction compared to oxidation.

Most investigations of multiply-reduced double-deckers have focused on phthalocyaninato ligands (Pcs), which are more easily reduced than porphyrins owing to their lower LUMO energy. Notably, Gonidec et al. demonstrated the magnetic properties of one- and two-electron-reduced bis(phthalocyaninato) complexes with perfluoroalkyl substituents in frozen solution,^[15] and Konarev et al. succeeded in isolating and structurally characterizing the dianion [Tb(Pc)₂]^{2–} in the solid state.^[16]

For porphyrin double-decker complexes, the situation is considerably different from that of phthalocyanine analogues. While cyclic voltammetry studies have demonstrated that reduction of [M^{III}(por)₂][–] is possible,^[6,21] isolation and detailed characterization of these multiply-reduced porphyrin double-decker species have not been achieved. Similar limitations exist for tetravalent metal (Zr, Hf, Th) porphyrin double-deckers, despite their somewhat enhanced reducibility compared to trivalent rare-earth complexes.^[6,22] Thus, despite electrochemical evidence for accessible multiply-reduced states in porphyrin double-deckers, the isolation and comprehensive characterization of these species represent a significant gap in this field.

To access multiply-reduced porphyrin double-decker complexes, β -tetracyanoporphyrin (CNTPP) was employed as the ligand. CNTPP is characterized by four electron-withdrawing cyano groups at the β -positions, which substantially lower the LUMO energy and render the ligand highly susceptible to reduction.^[23–35] Compared to TPP, the first reduction potential of CNTPP ligand is approximately 1 V more positive, indicating its remarkable electron-accepting ability.^[36] This property has been exploited in various applications, including incorporation into artificial photosynthetic systems and as sensitizers in photoelectrochemical devices.^[29–31,34]

Furthermore, our group previously demonstrated that CNTPP and analogues can undergo two-electron reduction with the mild reducing agent, hydrazine monohydrate, to generate a stable isophlorin species.^[37–39] This reduced form possesses a 20π electron system and exhibits antiaromatic character, as evidenced by significant upfield shifts in the ¹H NMR spectra and theoretical calculations. The structure was unambiguously confirmed by single-crystal X-ray diffraction. This exceptional

reduction capability of CNTPP to form a stable antiaromatic species, combined with its ability to form stable complexes with rare-earth ions, makes it an ideal candidate for generating multiply-reduced double-decker complexes. If a double-decker complex could be reduced by four electrons, it would result in the stacking of two 20π electron systems, leading to experimental studies of stacked-ring aromaticity (Figure 4.2).

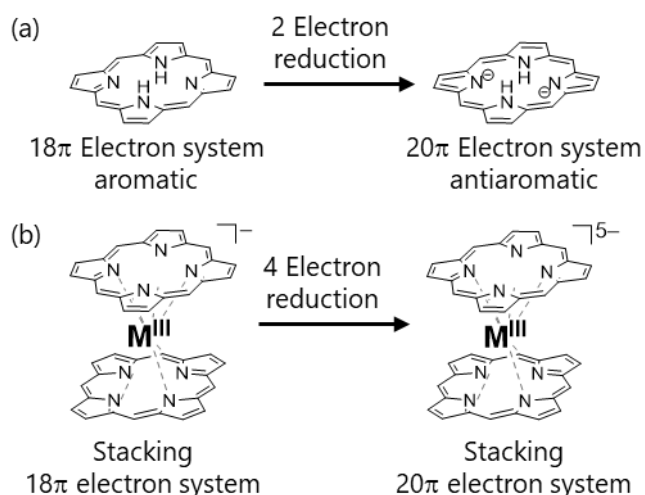


Figure 4.2 Chemical structures of (a) 2 electron reduction of porphyrin, forming 20π antiaromatic system and (b) four electron reduction of porphyrin double-decker complex, forming stacking 20π antiaromatic system.

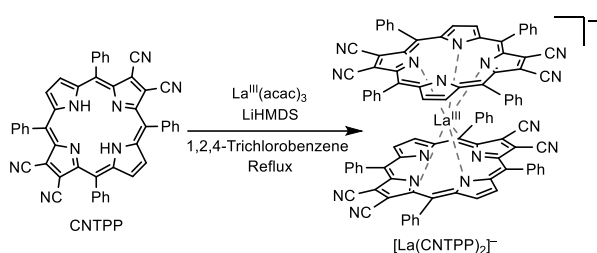
In this chapter, the synthesis, structural characterization, and electrochemical properties of lanthanum(III) β -tetracyanoporphyrin double-decker complexes $[\text{La}(\text{CNTPP})_2]^-$ was reported (Scheme 4.1). La^{III} was selected due to its diamagnetic nature, which enables detailed structural analysis by NMR spectroscopy. The complex was successfully isolated as a monoanion species and characterized by single-crystal X-ray diffraction, cyclic voltammetry, and variable-temperature NMR spectroscopy. These complexes exhibit remarkably high reduction potentials and can undergo four-electron reduction. Moreover, the reduced species was characterized by UV-vis/NIR spectroelectrochemistry and chemical reduction methods, providing spectroscopic evidence for the formation of multiply-reduced states.

4.2 Results and discussion

4.2.1 Synthesis and Isolation of β -Tetracyanoporphyrin Double-Decker Complexes

The desired La^{III} double-decker complex was synthesized by deprotonation of CNTPP with strong base (LiHMDS) followed by reaction with $\text{La}(\text{acac})_3$ under reflux (Scheme 4.1). MALDI-TOF MS analysis of the crude product revealed a peak at m/z values corresponding to the $[\text{La}(\text{CNTPP})_2]^-$.

Subsequent cation exchange with either tetrabutylammonium (NBu_4^+) or tetraphenylphosphonium (PPh_4^+) ions afforded the complex as the corresponding salt in 40% yield (for the NBu_4 salt). The complex was fully characterized by ^1H NMR spectroscopy, mass spectrometry, and single-crystal X-ray diffraction analysis. Notably, the complex was isolated as the monoanion form rather than as a protonated neutral form. This behavior contrasts with that of many rare-earth double-deckers bearing conventional porphyrin ligands, which often afford protonated neutral forms upon isolation. The preference for the monoanion form can be attributed to the reduced basicity of the porphyrin inner nitrogen atoms due to the strong electron-withdrawing effect of the four cyano groups at the β -positions, which disfavors protonation and stabilizes the anion form.



Scheme 4.1 Synthesis of $[\text{La}(\text{CNTPP})_2]^-$.

Attempts to synthesize the Y^{III} analogue under similar conditions were unsuccessful, with ^1H NMR and MS analyses of the crude products showing no evidence of complex formation. This result can be attributed to the smaller ionic radius of Y^{III} compared to La^{III} (Y^{3+} : 1.02 Å vs. La^{3+} : 1.16 Å for eight-coordinate ions). The reduced metal-ligand distance in a hypothetical yttrium complex would increase the steric repulsion between the bulky β -tetracyano-substituted porphyrin ligands, preventing complex formation.

4.2.2 Crystal Structure Analysis

Single crystals of $(\text{PPh}_4)[\text{La}(\text{CNTPP})_2]$ suitable for X-ray diffraction analysis were obtained by slow diffusion of hexane into a chloroform solution of the complex. The complex crystallizes in the monoclinic space group $C2/c$, and the molecular structure exhibits a typical sandwich-like double-decker geometry (Figure 4.3a–c). Selected structural parameters are summarized in Table 4.1 and compared with those of the $[\text{La}(\text{TPP})_2]^-$ complex (Figure 4.3d–f).

The average La-N bond length to the pyrrole rings bearing the CN groups is 2.620(2) Å while that to the unsubstituted rings is 2.577(2) Å. These structural features are attributed to the strong electron-withdrawing properties of the cyano groups on the porphyrin periphery; similar trends were observed in our previously reported tin complexes.^[39]

Table 4.1 Selected structural data for [La(CNTPP)₂][−] and [La(TPP)₂][−].^[a]

		[La(CNTPP) ₂] [−]	[La(TPP) ₂] [−]
Bond lengths [Å]	La–N _{CN} -pyrrole	2.620(2)	–
	La–N _H -pyrrole	2.577(2)	2.594(8)
Metal displacement [Å]^[b]	from N ₄ plane	1.555(1)	1.544(1)
	from core-24-atom plane	1.836(1)	1.827(1)
Mean plane deviation [Å]	N ₄ plane	0.03	0.02
	core-24-atom plane	0.32	0.23
Azimuthal rotation angle ϕ [°]		32.9	37.3

[a] For parameters with multiple crystallographically inequivalent sites, average values are reported unless the individual values differ significantly, in which case they are listed separately. [b] Vertical distance from La to the specified mean plane. [c] Dihedral angle between the pyrrole ring and N₄ mean plane.

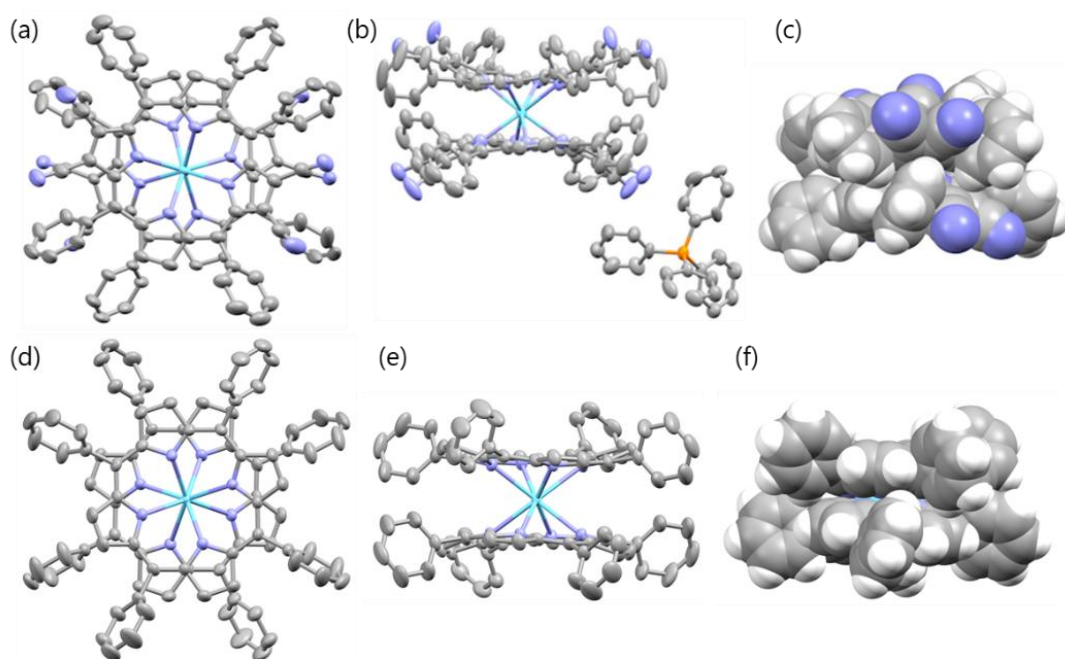


Figure 4.3 X-ray crystal structure of (PPh₄)[La(CNTPP)₂] and [La(TPP)₂][−]. C = gray, H = white, N = blue, La = pale blue, and P = orange. (a) Top view of (PPh₄)[La(CNTPP)₂] with thermal ellipsoid representations (50 % probability level). Solvated molecules, H atoms, and PPh₄⁺ are omitted for clarity. (b) Side view of (PPh₄)[La(CNTPP)₂] with thermal ellipsoid representations (50 % probability level). Solvated molecules and H atoms are omitted for clarity. (c) Side view of (PPh₄)[La(CNTPP)₂] with space-filling style. Solvated molecules and PPh₄⁺ are omitted for clarity. (d) Top view and (e) side view of [La(TPP)₂][−] with thermal ellipsoid representations (50 % probability level). Solvated molecules, H⁺ atoms and cations are omitted for clarity. (f) Side view of (PPh₄)[La(CNTPP)₂] with space-filling style. Solvated molecules and cations are omitted for clarity.

The notable structural feature of $[\text{La}(\text{CNTPP})_2]^-$ is the pronounced dome-shaped distortion of the ligands. Specifically, the pyrrole rings bearing the cyano groups are tilted significantly from the mean plane defined by the core 4 nitrogen atoms, with a tilt angle of 27° . This tilt angle is larger than that of the pyrrole ring without CN substituent (4.9°) or in $[\text{La}(\text{TPP})_2]^-$ (6.8° and 20°). The mean plane deviation (MPD) value defined by the core 24 atoms of the porphyrin macrocycles is $0.32 \text{ \AA}$ for $[\text{La}(\text{CNTPP})_2]^-$, significantly larger than the $0.23 \text{ \AA}$ observed for $[\text{La}(\text{TPP})_2]^-$, indicating greater deviation from planarity. This pronounced distortion can be attributed to steric repulsion between the *meso*-phenyl groups of one porphyrin ring and the cyano substituents on the adjacent porphyrin ring (Figure 4.3c).

The relative orientation of the two porphyrin rings is also of interest. In the structure of $[\text{La}(\text{CNTPP})_2]^-$, the two porphyrin rings are azimuthally rotated relative to each other by ca. 33° ; thus, the molecular structure of $[\text{La}(\text{CNTPP})_2]^-$ exhibits pseudo- D_2 symmetry. This rotation angle is smaller than that observed in $[\text{La}(\text{TPP})_2]^-$ (37°).

An ideal rotation angle of 45° for the monoanion form of double-decker complexes bearing C_4 symmetrical porphyrin ligands has been established through crystallographic studies and theoretical calculations.^[10,40,41] The deviation from 45° observed in the present $[\text{La}(\text{CNTPP})_2]^-$ structure (33°) and $[\text{La}(\text{TPP})_2]^-$ structure (37°) prompted to investigate whether this represents a true energy minimum or a crystallization artifact. Quantum chemical calculations were performed to investigate the most stable conformations of $[\text{La}(\text{CNTPP})_2]^-$ and $[\text{La}(\text{TPP})_2]^-$ (Figure 4.4). The calculated azimuthal rotation angle for $[\text{La}(\text{CNTPP})_2]^-$ was 32° , showing good agreement with the experimentally observed structure. This confirms that the ca. 33° rotation angle represents the true energy minimum for this complex, not a crystallization effect. In contrast, the azimuthal rotation angle of $[\text{La}(\text{TPP})_2]^-$ was 44° . This is consistent with other reported monoanion forms of porphyrin double-decker complexes.^[10,40,41] The deviation from 45° in the crystal structure of $[\text{La}(\text{TPP})_2]^-$ (37°) is therefore attributed to crystallization effects.

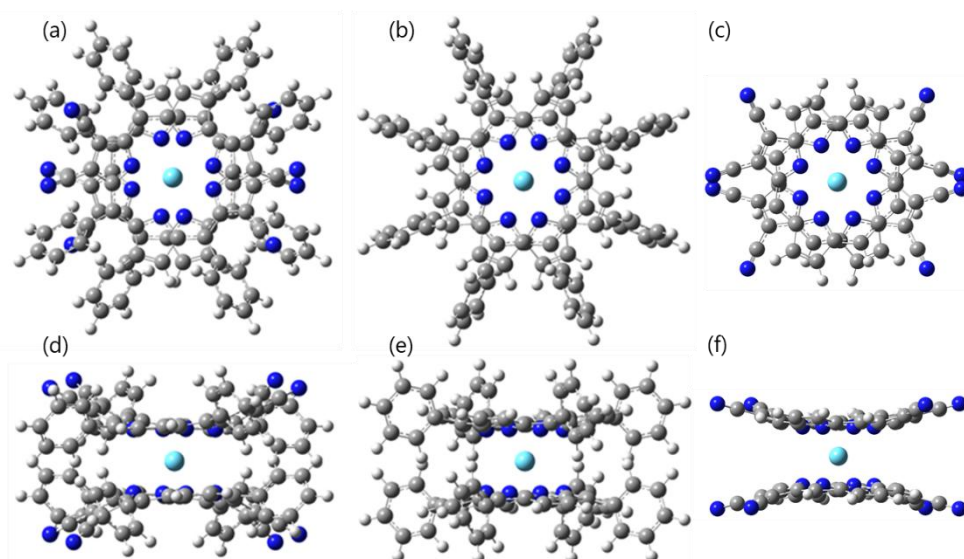


Figure 4.4 Optimized structures of lanthanum double-deckers. (a) $[\text{La}(\text{CNTPP})_2]^-$ top view, (b) $[\text{La}(\text{TPP})_2]^-$ top view, (c) $[\text{La}(\text{CNPor})_2]^-$ top view, (d) $[\text{La}(\text{CNTPP})_2]^-$ side view, (e) $[\text{La}(\text{TPP})_2]^-$ side view, and (f) $[\text{La}(\text{CNPor})_2]^-$ side view.

To elucidate the origin of the reduced rotation angle in $[\text{La}(\text{CNTPP})_2]^-$, additional calculations on a simplified model system lacking the *meso*-phenyl substituents were performed. The calculated rotation angle for this phenyl-free model was 46.7° , remarkably close to the ideal 45° and essentially identical to that of $[\text{La}(\text{TPP})_2]^-$. This result demonstrates that the electron-withdrawing cyano groups have negligible influence on the rotation angle through electronic effects. Instead, the 33° angle in $[\text{La}(\text{CNTPP})_2]^-$ arises primarily from steric repulsion between the *meso*-phenyl groups and the β -cyano substituents on the adjacent porphyrin ring, as evidenced by the pronounced dome-shaped distortion discussed above.

4.2.3 UV-vis/NIR Absorption Spectra

The UV-vis/NIR absorption spectrum of $[\text{La}(\text{CNTPP})_2]^-$ in CH_2Cl_2 exhibits a strong Soret band at 441 nm and weak and broad Q bands at 608 and 740 nm (Figure 4.5). These features closely resemble those of the free CNTPP ligand, which exhibits split Soret bands at 439 and 450 nm and Q bands between 550 nm and 800 nm. Notably, no absorption band was observed in the near-infrared region from 900 nm to 1500 nm, which is characteristic of the monoanion form.^[6]

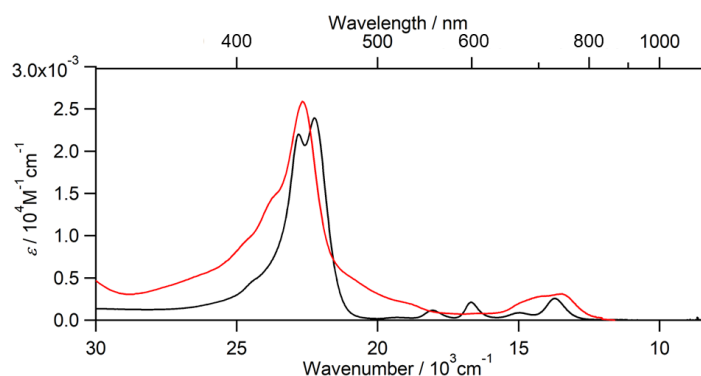


Figure 4.5 UV-vis/NIR absorption spectra of $\text{NBu}_4[\text{La}(\text{CNTPP})_2]$ in CH_2Cl_2 (red) and CNTPP in CH_2Cl_2 (black).

4.2.4 Electrochemical Properties

The electrochemical properties of $\text{NBu}_4[\text{La}(\text{CNTPP})_2]$ were investigated by cyclic and differential pulse voltammetry in CH_2Cl_2 and DMSO containing 0.1 M tetrabutylammonium hexafluorophosphate (TBAPF_6) as the supporting electrolyte (Table 4.2, Figures 4.6 and 4.7). All potentials were referenced to the ferrocene/ferrocenium (Fc/Fc^+) couple.

In CH_2Cl_2 , $[\text{La}(\text{CNTPP})_2]^-$ exhibited three reversible reduction waves at -1.02 , -1.22 , and -1.59 V, and one quasi-reversible reduction at -1.85 V, corresponding to the $(-1/-2)$, $(-2/-3)$, $(-3/-4)$, and $(-4/-5)$ couples. In addition to these reduction processes, two reversible and one irreversible oxidation waves were also observed. In DMSO, the corresponding reduction waves were observed at -0.78 , -1.00 V, -1.42 , and -1.66 V, shifted approximately 0.2 V to more positive potentials compared with those in CH_2Cl_2 , indicating enhanced stabilization of the reduced species in this polar solvent. These results demonstrate four-electron reduction capability, which is unprecedented for trivalent rare-earth porphyrin double-decker complexes.

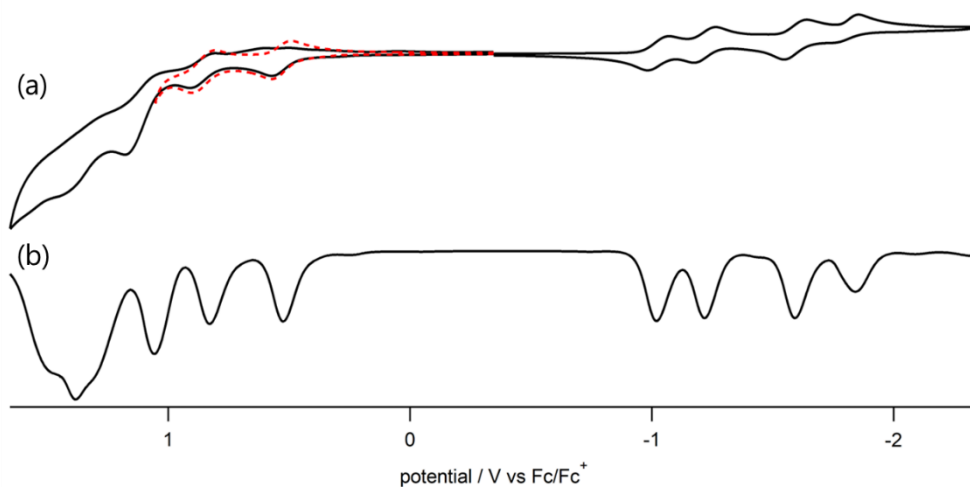


Figure 4.6 (a) Cyclic and (b) differential pulse voltammogram of $\text{NBu}_4[\text{La}(\text{CNTPP})_2]$ in CH_2Cl_2 .

For comparison, the free CNTPP ligand exhibited two reversible reduction waves at -0.75 V and -1.05 V in CH_2Cl_2 , corresponding to the formation of the monoanion and antiaromatic dianion species.^[38] The reduction potentials of $[\text{La}(\text{CNTPP})_2]^-$ are more negative than those of the free ligand, reflecting the additional electron density and electrostatic repulsion in the anionic double-decker framework.

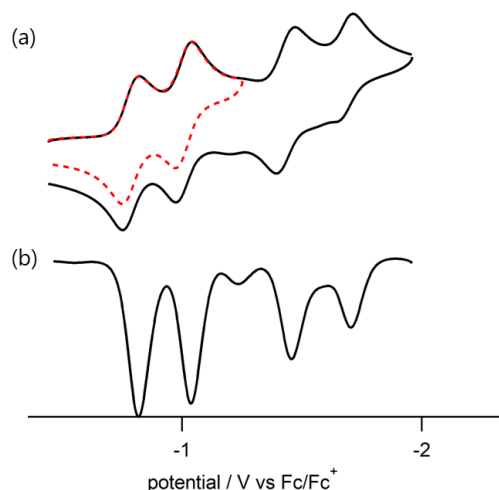


Figure 4.7 (a) Cyclic and (b) differential pulse voltammogram of $\text{NBu}_4[\text{La}(\text{CNTPP})_2]$ in DMSO.

Table 4.2 Redox Potentials of $[\text{La}(\text{CNTPP})_2]^n$ ^[a] and $[\text{La}(\text{TPP})_2]^n$ (V vs Fc/Fc^+)^[b]

		+2/+1	+1/0	0/-1	-1/-2	-2/-3	-3/-4	-4/-5
$\text{NBu}_4[\text{La}(\text{CNTPP})_2]$	CH_2Cl_2	1.05 ^[f]	0.83	0.53	-1.02	-1.22	-1.59	-1.85 ^[g]
	DMSO	— ^[c]	— ^[c]	— ^[c]	-0.78	-1.00	-1.42	-1.66 ^[g]
$\text{NBu}_4[\text{La}(\text{TPP})_2]$ ^[e]	CH_2Cl_2	0.72	0.05	-0.30	— ^[d]	— ^[d]	— ^[d]	— ^[d]
	DMF	— ^[d]	0.20	-0.07	-2.06	-2.35	— ^[d]	— ^[d]

[a] Redox potentials were determined by differential pulse voltammetry. [b] From ref. 6. [c] Out of potential window. [d] Not reported in the reference. [e] Potentials in ref. 6 were originally reported vs. SCE and have been converted to V vs. Fc/Fc^+ using the relationship: $E(\text{vs. Fc}/\text{Fc}^+) = E(\text{vs. SCE}) - 0.46$ V. [f] Irreversible peak. [g] Quasi-reversible peak.

Remarkably, the reduction potentials of $[\text{La}(\text{CNTPP})_2]^-$ are approximately 1.3 V more positive than those of $[\text{La}(\text{TPP})_2]^-$ (i.e., easier to reduce). Buchler et al. reported reduction potentials of -2.06 and -2.35 V (vs. Fc/Fc^+) corresponding to $(-1/-2)$ and $(-2/-3)$ couples for $[\text{La}(\text{TPP})_2]^n$ in DMF.^[6] In comparison, the corresponding processes for $[\text{La}(\text{CNTPP})_2]^-$ occur at -0.78 V and -1.00 V in DMSO, representing shifts of approximately 1.3 V toward more positive potentials. This dramatic

shift demonstrates the strong electron-withdrawing effect of the β -cyano substituents, which significantly lowers the LUMO energy and facilitates multiple-electron reduction.

4.2.5 Spectroelectrochemical and Chemical Reduction Studies

To characterize the reduced species of $[\text{La}(\text{CNTPP})_2]^-$, UV-vis/NIR spectroelectrochemical experiments were performed in DMSO. Upon two-electron reduction of $[\text{La}(\text{CNTPP})_2]^-$ at -1.3 V, the absorption bands at 441, 608, and 740 nm decreased in intensity with slight shifts, while new absorption bands appeared at 972 and 1074 nm (Figure 4.8a). These spectral changes are consistent with the formation of the trianion $[\text{La}(\text{CNTPP})_2]^{3-}$ at a potential of -1.3 V. Further reduction at -2.1 V resulted in disappearance of the characteristic peaks for $[\text{La}(\text{CNTPP})_2]^{3-}$ at 972 and 1074 nm and increased intensity of peaks at 601 and 655 nm (Figure 4.8b). Because the fourth reduction process is quasi-reversible as judged by CV measurements, the complete formation of $[\text{La}(\text{CNTPP})_2]^{5-}$ could not be definitively confirmed.

Chemical reduction of $(\text{NBu}_4)[\text{La}(\text{CNTPP})_2]$ using cobaltocene (CoCp_2) resulted in an absorption spectrum resembling that obtained from spectroelectrochemical experiments at -1.3 V (Figure 4.8b).

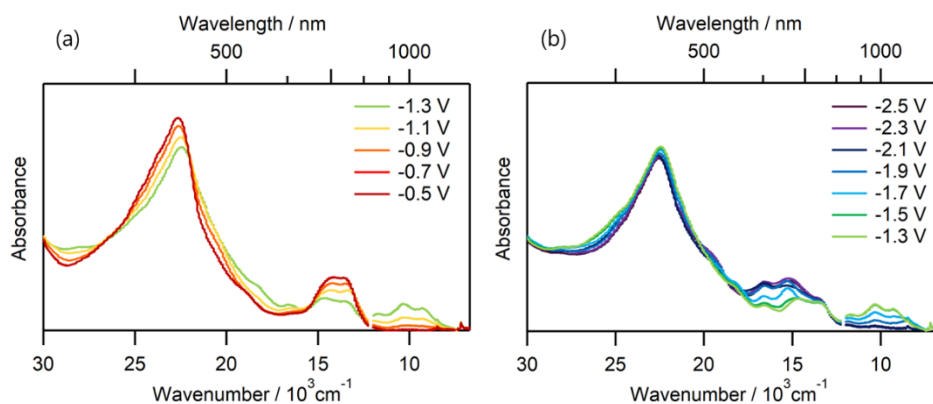


Figure 4.8 UV-vis/NIR absorption spectra recorded during the electrochemical reduction of $[\text{La}(\text{CNTPP})_2]^-$ in DMSO. (a) Starting from $[\text{La}(\text{CNTPP})_2]^-$ under -0.5 V to -1.3 V and (b) starting from two-electron reduced $[\text{La}(\text{CNTPP})_2]^-$ under -1.3 V to -2.5 V.

Because isolation and further experimental characterization of the trianion $[\text{La}(\text{CNTPP})_2]^{3-}$ proved unsuccessful, quantum chemical calculations were used to support its formation. DFT calculations revealed that $[\text{La}(\text{CNTPP})_2]^{3-}$ does not adopt a closed-shell singlet (CS) configuration but instead exhibits significant diradical character. The open-shell singlet (OS) state is more stable than the CS state by $13.8 \text{ kcal mol}^{-1}$, with a diradical character index y_0 of 0.93 (Figure 4.9).

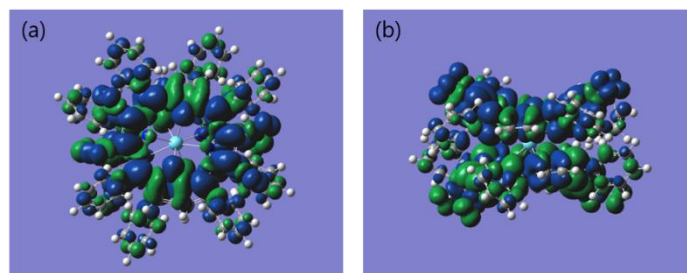


Figure 4.9 Spin density maps of $[\text{La}(\text{CNTPP})_2]^{3-}$ (OS). (a) Top view and (b) side view.

Furthermore, the energy difference between the OS and triplet (T) states is negligible ($\Delta E_{\text{ST}} = 0.01 \text{ kcal mol}^{-1}$, with the triplet being slightly more stable), indicating that the OS and T states are essentially isoenergetic. TD-DFT calculations predict nearly identical absorption spectra for both the OS and T states (Figure 4.10). Importantly, the calculated spectral changes upon reduction from the monoanion to the trianion are in good agreement with the experimental observations from spectroelectrochemistry and chemical reduction experiments, supporting the assignment of the experimentally observed spectra to $[\text{La}(\text{CNTPP})_2]^{3-}$. The failure to observe meaningful ^1H NMR signals for the reduced species is consistent with the predicted diradical character.

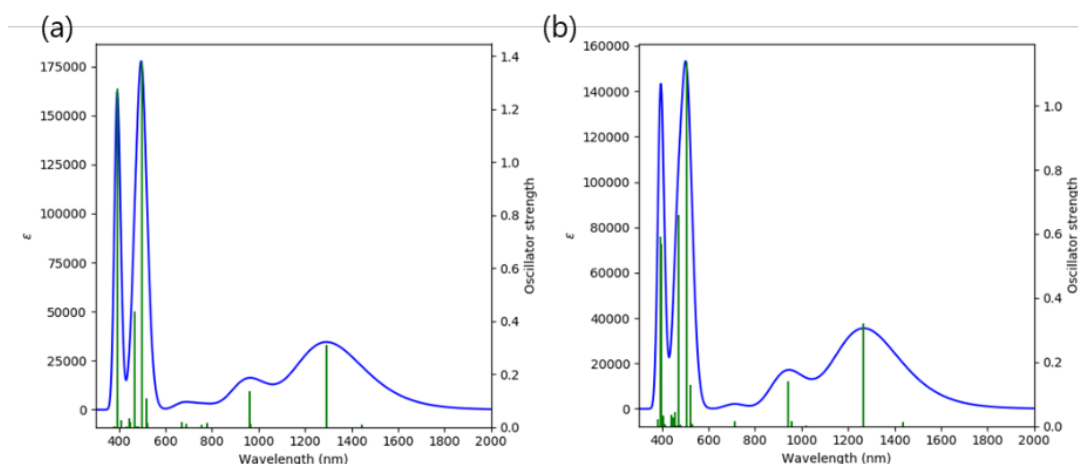


Figure 4.10 Calculated (TDDFT) UV-vis/NIR absorption spectra of $[\text{La}(\text{CNTPP})_2]^{3-}$. (a) Open-shell singlet and (b) triplet.

4.2.6 NMR Spectroscopy and Rotational Dynamics

The ^1H NMR spectrum of $[\text{La}(\text{CNTPP})_2]^-$ in CDCl_3 exhibits a total of 12 distinct, sharp peaks at 25°C (Figure 4.11), all of which were unambiguously assigned using two-dimensional NMR techniques (COSY, Figure 4.12). The spectrum revealed two sets of β -proton signals and two sets of phenyl resonances corresponding to the different chemical environments, consistent with the D_2

symmetry observed in the solid-state structure. The observation of well-resolved, distinct peaks for all chemically non-equivalent protons indicates that the porphyrin ligand rotation is slow on the NMR timescale at room temperature. This behavior contrasts sharply with previously reported lanthanum porphyrin double-decker complexes such as $[\text{La}(\text{TPP})_2]^-$ and $[\text{La}(\text{OEP})_2]^-$, which exhibit rapid ligand rotation that causes signal averaging even at room temperature or below, preventing quantitative measurement of rotational barriers by NMR methods.^[42]

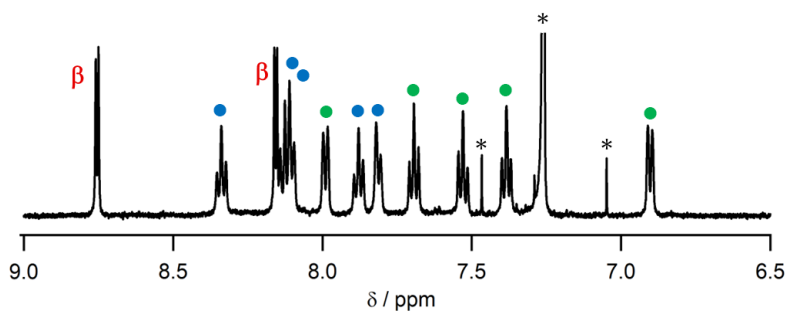


Figure 4.11 ^1H NMR spectrum (500 MHz) of $(\text{NBu}_4)[\text{La}(\text{CNTPP})_2]$ in CDCl_3 at 25 °C. Asterisks indicate the solvent peaks, and the circles of the same color represent peaks derived from the same phenyl group.

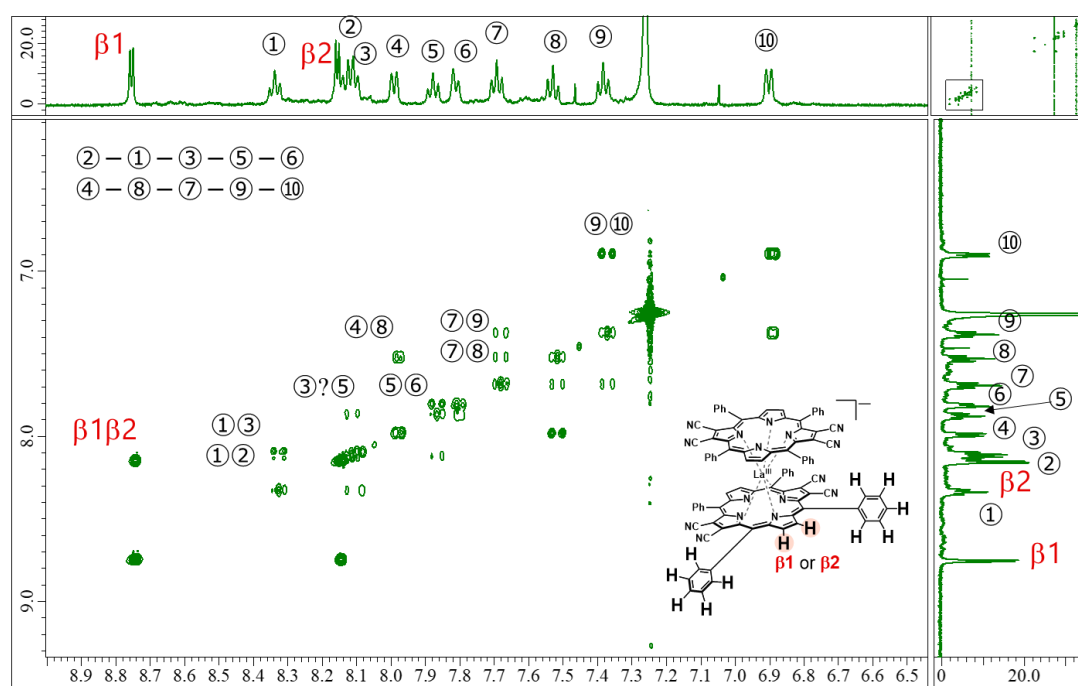


Figure 4.12 ^1H COSY NMR (500 MHz, CDCl_3) spectrum of $\text{NBu}_4[\text{La}(\text{CNTPP})_2]$.

To investigate the rotational dynamics, variable-temperature (VT) ^1H NMR measurements were performed in $[D_2]1,1,2,2\text{-tetrachloroethane}$ (Figure 4.13). Upon heating from 25 °C to 70 °C,

peak broadening was observed for both the β -proton and phenyl proton peaks, indicating the onset of exchange processes involving rotation of the entire porphyrin macrocycles. Further heating to 130 °C resulted in extensive peak broadening, although complete coalescence to averaged signals was not achieved, indicating a substantial rotational barrier.

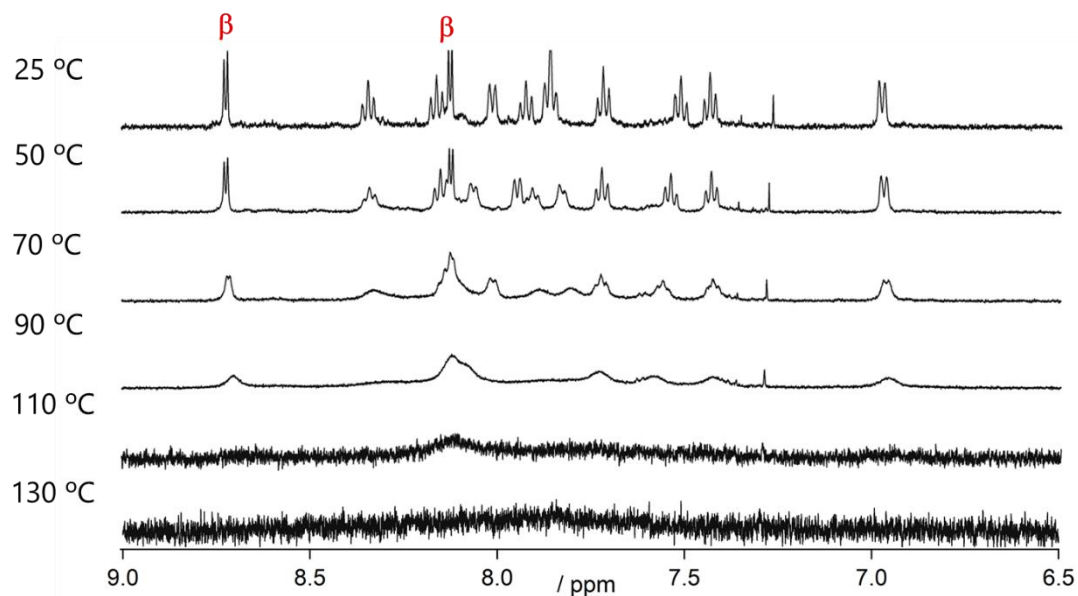


Figure 4.13 VT- ^1H NMR (500 MHz, $[\text{D}_2]$ 1,1,2,2-tetrachloroethane) spectra of $\text{NBu}_4[\text{La}(\text{CNTPP})_2]$.

To quantitatively assess the rotational barrier, 1D VT Exchange Spectroscopy (EXSY) NMR measurements were carried out at 298, 313, 323, and 333 K. These measurements yielded rotation rate constants of 0.64, 1.54, 3.89, and 8.17 s^{-1} at 298, 313, 323, and 333 K, respectively (Table 4.3). The rate constant at room temperature is approximately two orders of magnitude slower than previously reported for the lanthanum double-decker complex.^[42] The Eyring plot of the rate constants gave the kinetic parameters as $\Delta H^\ddagger = 57.9 \pm 5.2 \text{ kJ mol}^{-1}$ ($13.9 \pm 1.3 \text{ kcal mol}^{-1}$), $\Delta S^\ddagger = -55 \pm 17 \text{ J mol}^{-1} \text{ K}^{-1}$ ($-13.2 \pm 4.0 \text{ cal mol}^{-1} \text{ K}^{-1}$), and $\Delta G_{298 \text{ K}}^\ddagger = 74.3 \pm 7.2 \text{ kJ mol}^{-1}$ ($17.8 \pm 1.7 \text{ kcal mol}^{-1}$) (Figures 4.14 and 4.15).

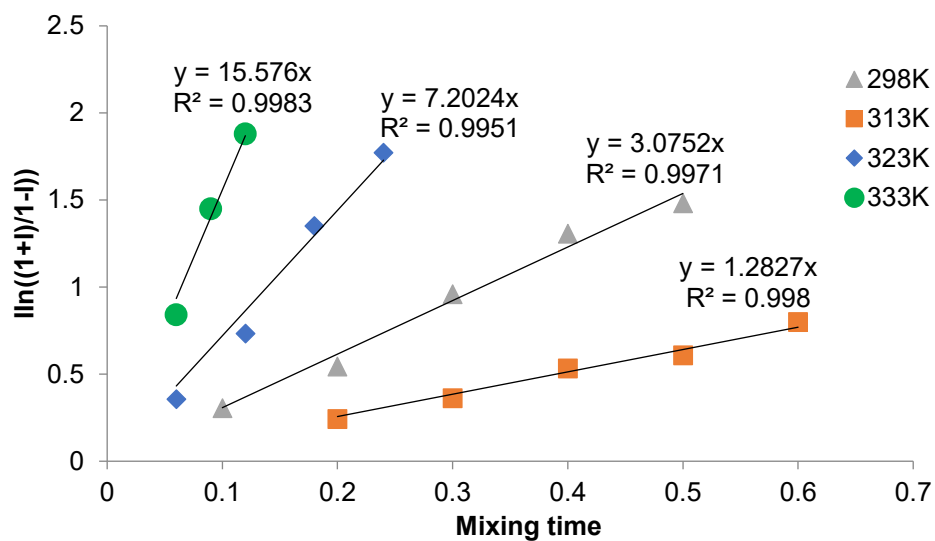


Figure 4.14 Plots of the EXSY results of $(\text{NBu}_4)[\text{La}(\text{CNTPP})_2]$ to determine exchange rate constants.

Table 4.3 Exchange rate constants determined by EXSY measurements.

T (K)	$2k$ (s^{-1})
298	1.28 ± 0.02
313	3.08 ± 0.08
323	7.79 ± 0.37
333	16.3 ± 0.45

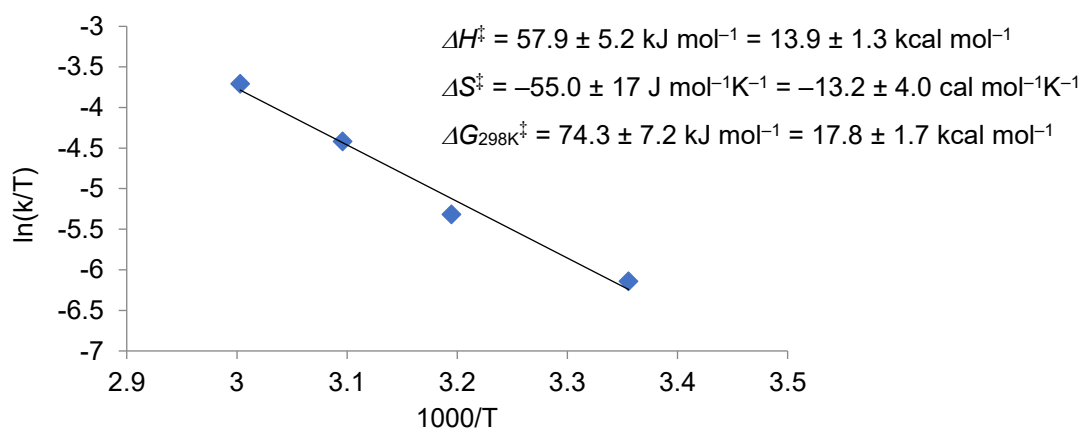


Figure 4.15 Eyring plot.

The significantly higher rotational barrier observed for $[\text{La}(\text{CNTPP})_2]^-$ may originate from two possible factors: (1) increased steric repulsion between the *meso*-phenyl groups and the bulky cyano substituents on the adjacent porphyrin ring, or (2) electronic effects induced by the strong

electron-withdrawing cyano groups that alter π - π interactions between the two porphyrin rings. To evaluate the contribution of electronic effects, DFT calculations were performed on a simplified model system lacking the *meso*-phenyl substituents, as described in the Crystal Structure Analysis section. The calculated rotational energy profile for this model system shows an energy minimum at a rotation angle of 46° and two transition states at 0° (D_{2h} symmetry) and 90° (D_{2d} symmetry), with corresponding activation barriers of 37.2 kJ mol^{-1} ($8.90 \text{ kcal mol}^{-1}$) and 24.5 kJ mol^{-1} ($5.86 \text{ kcal mol}^{-1}$), respectively (Figure 4.16).

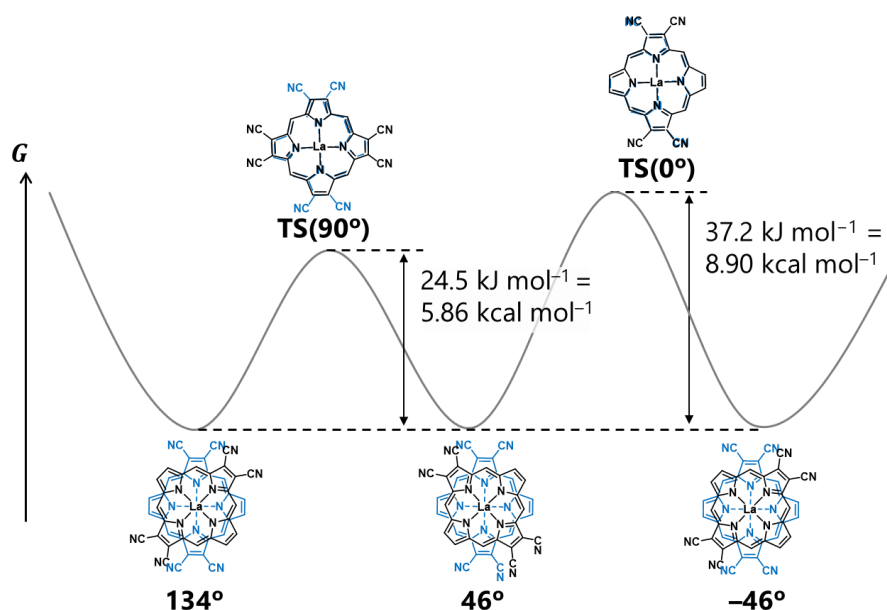


Figure 4.16 Transition states and energy barrier of azimuthal rotation process of the ligands in $[\text{La}(\text{CNPPor})_2]^-$. The three stable states at azimuthal rotation angles of -46° , 46° , and 134° are energetically equivalent due to the D_2 molecular symmetry.

Both barriers are significantly lower than the experimentally obtained value (74.4 kJ mol^{-1} , $17.8 \text{ kcal mol}^{-1}$), indicating that the electronic effect of the cyano groups contributes minimally to the rotational barrier. Therefore, the primary factor responsible for the slow rotation in $[\text{La}(\text{CNTPP})_2]^-$ is the steric repulsion between the *meso*-phenyl groups and the cyano substituents. This interpretation is further supported by the pronounced dome-shaped distortion observed in the crystal structure (Figure 3), which directly reflects the steric congestion within the double-decker framework.

4.3 Summary

Lanthanum(III) β -tetracyanoporphyrin double-decker complexes $[\text{La}(\text{CNTPP})_2]^-$ has successfully synthesized and characterized by ^1H NMR spectroscopy, single-crystal X-ray diffraction, cyclic voltammetry, and variable-temperature NMR spectroscopy. $[\text{La}(\text{CNTPP})_2]^-$ exhibited unprecedented four-electron reduction capability, reaching the pentaanion state $[\text{La}(\text{CNTPP})_2]^{5-}$. This

represents the first example of reversible four-electron reduction in trivalent rare-earth porphyrin double-decker systems. The strategic incorporation of electron-withdrawing cyano groups shifts the reduction potentials by approximately 1.3 V toward more positive values compared to conventional $[\text{La}(\text{TPP})_2]^-$ complexes, enabling access to highly reduced states (-0.78 , -1.00 , -1.42 , and -1.66 V vs. Fc/Fc^+ in DMSO) that were previously unattainable in porphyrin-based double-decker systems.

Structural characterization revealed that the complexes adopt the monoanion form with an azimuthal rotation angle of 33° and pronounced dome-shaped distortion, both arising from steric interactions between the *meso*-phenyl groups and β -cyano substituents. Investigation of rotational dynamics showed an unusually high activation barrier ($\Delta G^\ddagger = 17.8 \text{ kcal mol}^{-1}$ at 298 K), an origin that DFT calculations attribute primarily to steric repulsion rather than electronic effects associated with the cyano groups.

The ability to access multiply-reduced states while maintaining structural integrity opens new possibilities in molecular electronics, catalysis, and energy conversion systems. Building on our previous studies on 20π antiaromatic isophlorins generated by two-electron reduction of CNTPP,^[38,39] the four-electron reduction capability suggests the possibility of generating stacked antiaromatic structures with unique electronic properties. Furthermore, double-decker complexes with similar D_2 symmetry have been reported to possess high polarizability,^[43] which, combined with the tunable redox properties demonstrated here, makes these systems promising candidates for switchable molecular devices and nonlinear optical applications.

4.4 Experimental Section

4.4.1 Instrumental and Chemicals

La^{III} complex of tetraphenylporphyrin $[\text{La}(\text{TPP})(\text{TPPH})]^{[6]}$ were synthesized according to previously reported procedures. For ^{13}C NMR spectra, CDCl_3 and $[\text{D}_6]\text{acetone}$ ($\delta = 77.0$ and 29.8 ppm) were used as internal standards. All other instruments and chemicals are as described in Chapter 2.4.1. UV-vis spectroelectrochemical measurements were carried out using an optically transparent electrochemical (OTE) cell (modified quartz cuvette; optical path length, 0.5 mm). A three-electrode configuration consisting of a Pt gauze working electrode, a Pt wire counter electrode, and a silver wire pseudo-reference electrode. Ferrocene was used as the internal standard in all the electrochemical experiments, and the reported potentials were corrected for the Fc/Fc^+ couple.

4.4.2 Synthetic Procedures

Synthesis of Bis[7,8,17,18-tetracyano-5,10,15,20-tetraphenyl]porphyrinato]lanthanum(III) tetrabutylammonium salt $((\text{NBu}_4)[\text{La}(\text{CNTPP})_2])$

To a solution of CNTPP (72.5 mg, 0.101 mmol) in 1,2,4-trichlorobenzene (2.0 mL), LiHMDS (1 M

solution in toluene, 0.22 mL, 0.22 mmol) was added. The resultant solution was heated at 200 °C for 30 min under dark. After cooling to room temperature, La(acac)₃ (88.4 mg, 0.203 mmol) was added, and the solution was heated at 250 °C for 17 h. under dark. After cooling to room temperature, the solvent was removed, and the crude products were dissolved into methanol. A saturated solution of tetrabutylammonium bromide in methanol was gently poured into the resulting solution and left to stand for 3 h. The precipitated microcrystals of (NBu₄)[La(CNTPP)₂] were collected by filtration. The filtration was concentrated and dissolved in chloroform. A saturated solution of tetrabutylammonium bromide in methanol was gently poured into the resulting solution and left to stand for 3 h. Then, the precipitated microcrystals of (NBu₄)[La(CNTPP)₂] were collected by filtration and dried under vacuum to afford (NBu₄)[La(CNTPP)₂] as purple crystals. (31.5 mg, 0.0201 mmol, 40%). M.p. > 300 °C; ¹H NMR (500 MHz, CDCl₃): δ = 8.76 (d, *J* = 4.67 Hz, 4H; Por*H_b*), 8.34 (t, *J* = 7.25 Hz, 4H; Ph*H_m*), 8.15 (d, *J* = 3.91 Hz, 4H; Por*H_b*), 8.01–8.13 (m, 8H; Ph*H_o* and Ph*H_p*), 7.99 (d, *J* = 8.49 Hz, 4H; Ph*H_o*), 7.88 (t, *J* = 5.53 Hz, 4H; Ph*H_m*), 7.81 (d, *J* = 5.72 Hz, 4H; Ph*H_o*), 7.70 (t, *J* = 4.77 Hz, 4H; Ph*H_p*), 7.53 (t, *J* = 7.15 Hz, 4H; Ph*H_m*), 7.39 (t, *J* = 9.35 Hz, 4H; Ph*H_m*), 6.90 (d, *J* = 7.44 Hz, 4H; Ph*H_o*), 2.92 (m, 8H; ⁿBu), 1.43 (f, *J* = 3.59 Hz, 8H; ⁿBu), 1.25 (m, 8H; ⁿBu); 0.87 ppm (t, *J* = 7.41 Hz, 12H; ⁿBu); ¹³C NMR (125 MHz, acetone-*d*₆): δ = 153.9 (Cq), 153.1 (Cq), 147.7 (Cq), 147.0 (Cq), 141.4 (Cq), 141.1 (Cq), 139.5 (CH), 137.9 (CH), 137.0 (CH), 136.3 (CH), 134.7 (CH), 130.6 (CH), 129.8 (CH), 129.1 (CH), 128.8 (CH), 128.0 (CH), 127.8 (CH), 126.2 (Cq), 125.8 (Cq), 115.1 (Cq), 113.7 (Cq), 113.1 (Cq), 112.6 (Cq), 59.4 (t, *J* = 2.40 Hz, CH₂), 24.4 (CH₂), 20.3 (CH₂), 13.8 ppm (CH₃); HRMS(ESI): *m/z*: calcd for C₉₆H₄₈N₁₆La: 1563.332 [*M*][−]; found: 1563.332. elemental analysis calcd (%) for C₁₁₂H₈₄N₁₇La·H₂O: C 73.71, H 4.75, N 13.05; found: C 73.18, H 4.83, N 12.79; UV/vis (CH₂Cl₂): λ_{max} (Logε) = 321 (4.79), 441 (5.42), 608 (3.87), 740 (4.48) nm.

4.4.4 NMR Spectra of New Compounds

(NBu₄)[La(CNTPP)₂]

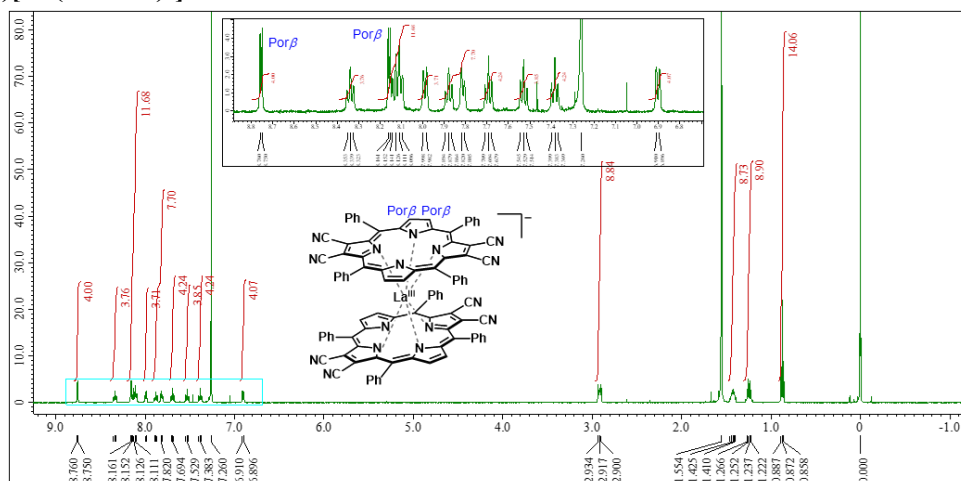


Figure E4.1 ¹H NMR spectrum in CDCl₃.

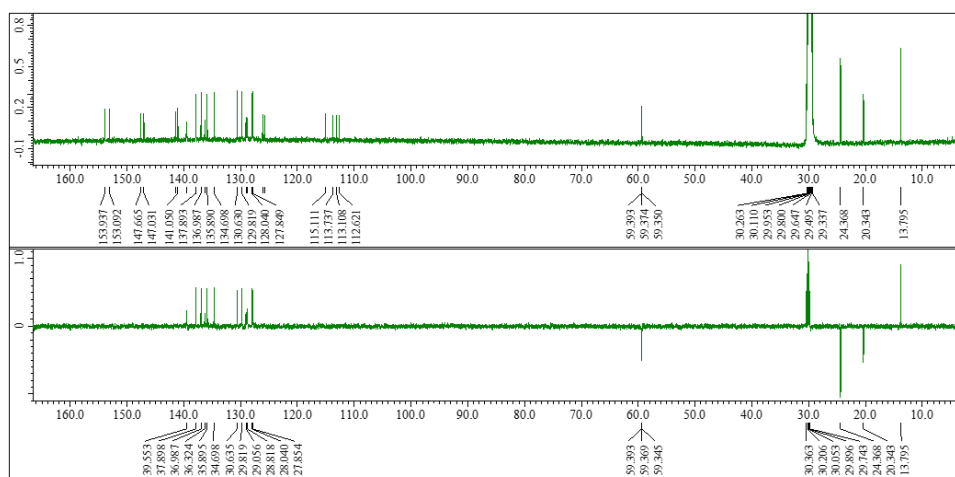


Figure E4.2 ¹³C NMR (above) and dept135 (down) spectra in [D₆]acetone.

4.4.5 X-ray Crystal Structure Determinations

Single-crystal X-ray diffraction data were collected on a Rigaku XtaLAB Synergy Custom diffractometer using multilayer mirror monochromated Mo-K α radiation ($\lambda = 0.71075$ Å) by the ω scan mode (for (DBU-H)[La(TPP)₂]), or a Rigaku XtaLAB P200 diffractometer using multilayer mirror monochromated Cu-K α radiation ($\lambda = 1.54184$ Å) by the ω scan mode (for (PPh₄)[La(CNTPP)₂]). For (PPh₄)[La(CNTPP)₂] and (DBU-H)[La(TPP)₂], solvent molecules and/or a counter ion were heavily disordered. Therefore, they were removed from the structure (and the corresponding F_0) using the SQUEEZE procedure^[44] implemented in the PLATON program suite. All other techniques and software are as described in Chapter 2.4.4. The crystallographic data is summarized in Table E4.1. Deposition Numbers 2518591 (for (PPh₄)[La(CNTPP)₂]) and 2518590 (for

(DBU-H)[La(TPP)₂]) contain the supplementary crystallographic data for these crystals. Single crystals of (PPh₄)[La(CNTPP)₂] suitable for X-ray diffraction study were obtained by slow diffusion of hexane into a solution of (PPh₄)[La(CNTPP)₂] in chloroform, while those of [La(TPP)₂][−] were obtained by slow vapor diffusion of methanol into a solution of [La(TPP)₂H] (just deprotonated by 1,8-diazabicyclo[5,4,0]undec-7-ene) in chloroform.

Table E4.1 Crystallographic data.

	(PPh ₄)[La(CNTPP) ₂] ^b	(DBU-H)[La(TPP) ₂] ^b
CCDC No.	2518591	2518590
empirical formula	C ₁₂₀ H ₆₈ LaN ₁₆ P·(CHCl ₃) ₂ ·(solvent) _m	C ₈₈ H ₅₆ N ₈ La·(DBU-H)·(solvent) _m ^c
formula weight	2142.52	1364.31
temperature / K	153(2)	223(2)
crystal system	Monoclinic	Monoclinic
space group	C2/c	C2/c
<i>a</i> / Å	32.7304(3)	21.0184(4)
<i>b</i> / Å	14.16280(10)	21.6713(4)
<i>c</i> / Å	26.0398(2)	19.0884(4)
α / deg	90	90
β / deg	99.1540(10)	91.102(2)
γ / deg	90	90
<i>V</i> / Å ³	2683.2(2)	8693.1(3)
<i>Z</i>	4	4
<i>D</i> (calcd) / g cm ^{−3}	1.194	1.042
μ / mm ^{−1}	4.545	0.534
<i>F</i> (000)	4352	2788
crystal size / mm ³	0.15 × 0.10 × 0.10	0.25 × 0.22 × 0.20
θ range for data collection / deg	3.407 to 74.957	1.709 to 31.090
index ranges	−38 ≤ <i>h</i> ≤ 40, −17 ≤ <i>k</i> ≤ 17, −32 ≤ <i>l</i> ≤ 32	−28 ≤ <i>h</i> ≤ 25, −29 ≤ <i>k</i> ≤ 25, −22 ≤ <i>l</i> ≤ 23
reflections collected	80239	45794
independent reflections	12047 [R(int) = 0.0482]	11024 [R(int) = 0.0397]
completeness	99.9%	100.0%
data / restraints / parameters	12047 / 6 / 775	11024 / 0 / 438
GOF on <i>F</i> ²	1.069	1.049
final <i>R</i> indices [<i>I</i> > 2σ(<i>I</i>)] ^a	<i>R</i> ₁ = 0.0610, <i>wR</i> ₂ = 0.1868	<i>R</i> ₁ = 0.0336, <i>wR</i> ₂ = 0.0864
<i>R</i> indices (all data) ^a	<i>R</i> ₁ = 0.0662, <i>wR</i> ₂ = 0.1931	<i>R</i> ₁ = 0.0386, <i>wR</i> ₂ = 0.0888
largest diff. peak and hole / e·Å ^{−3}	1.352 and −1.203	1.712 and −0.704

^a *R*₁ = $\sum||F_o| - |F_c|| / \sum|F_o|$, *wR*₂ = $[\sum[w(F_o^2 - F_c^2)^2] / \sum w(F_o^2)^2]^{1/2}$. ^b SQUEEZE program was used to remove the severely disordered components. ^c Structure of [DBU-H]⁺ could not be deduced from the data.

4.4.6 Other Experimental Details

1D ^1H EXSY spectra of $(\text{NBu}_4)[\text{La}(\text{CNTPP})_2]$ in $[\text{D}_2]$ tetrachloroethane were recorded on a JEOL EXZR-500 (500 MHz) spectrometer. A pulse sequence for 1D NOESY was employed. One of the β -proton peaks at ca. 8.77 ppm was selectively irradiated, and the other proton peak was observed as a correlation peak at ca. 8.13 ppm. Spectra were recorded under various mixing times (t_m). In each measurement, the peaks intensities of the irradiated and correlated peaks (I_{irr} and I_{cor}) were integrated. The rate constant k at each temperature was determined by the least-squares method from plots of $\ln\{(1+I)/(1-I)\}$ versus t_m according to the following equation:^[45]

$$\ln \frac{(1+I)}{(1-I)} = 2kt_m$$

where $I = I_{\text{cor}} / I_{\text{irr}}$. The plots and obtained k values are shown in Figure 4.14 and Table 4.3, respectively.

The kinetic parameters ($\Delta H^\ddagger$, $\Delta S^\ddagger$ and $\Delta G_{298\text{K}}^\ddagger$) were calculated by Eyring plot analysis of the obtained k values (Figure 4.15).

4.4.7 DFT Calculations

All calculations were carried out as described in Chapter 2.4.5. The geometries of monoanions were optimized using the DFT method at the CAM-B3LYP level. LANL2DZ basis set was used for the La atom and the 6-31+G(d,p) basis set was used for the other light atoms. For the coordinates of the optimized structure, see pp. S12–S25 (in <https://chemrxiv.org/engage/api-gateway/chemrxiv/assets/orp/resource/item/69569182900d745c43bc2327/original/supporting-information.pdf>). To confirm that the optimized geometries were at stable points (for ground states) or at saddle points (for transition states), frequency calculations were performed.

For the trianion $[\text{La}(\text{CNTPP})_2]^{3-}$, three electronic states were examined: closed-shell singlet (CS) using restricted CAM-B3LYP, open-shell singlet (OS), and triplet (T) states using unrestricted CAM-B3LYP. To reduce computational cost, geometry optimization and frequency calculations were performed using the LANL2DZ basis set for the La atom and the 6-31G(d,p) basis set (without diffuse functions) for the other atoms. Single-point energy calculations were subsequently performed using the LANL2DZ basis set for the La atom and the 6-31+G(d,p) basis set (with diffuse functions) for the other atoms. The stability of the unrestricted wavefunctions for the OS and T states was verified using the “stable” keyword. TD-DFT calculations were performed on the optimized structures with the inclusion of solvent effects (DMSO) using the polarizable continuum model (PCM).

Table E4.2 Summary of the TDDFT calculation of [La(CNTPP)₂]³⁻ (OS). (solvent = DMSO).

No.	Energy (cm ⁻¹)	Wavelength (nm)	Osc. Strength	Major contribution
1	6961.371	1436.499	0.0122	H-1(A)->LUMO(A) (50%), H-1(B)->LUMO(B) (50%)
2	7900.201	1265.791	0.3194	H-1(A)->LUMO(A) (48%), H-1(B)->LUMO(B) (48%)
3	9810.122	1019.355	0.0013	HOMO(A)->LUMO(A) (31%), HOMO(B)->LUMO(B) (31%)
4	10106.13	989.4987	0	HOMO(A)->LUMO(A) (31%), HOMO(B)->LUMO(B) (31%)
5	10445.69	957.333	0.0164	H-1(A)->L+1(A) (18%), H-1(B)->L+1(B) (18%)
6	10632.81	940.4854	0.1395	H-1(A)->L+1(A) (19%), H-1(B)->L+1(B) (19%)
7	11199.01	892.9362	0	HOMO(A)->LUMO(A) (19%), HOMO(B)->LUMO(B) (19%)
8	11570.02	864.3025	0	HOMO(A)->LUMO(A) (18%), HOMO(B)->LUMO(B) (18%)
9	14023.56	713.0856	0.0172	H-3(A)->LUMO(A) (19%), H-3(B)->LUMO(B) (19%),
10	14063.89	711.0408	0.003	H-3(A)->LUMO(A) (19%), H-3(B)->LUMO(B) (19%)
11	18911.28	528.7849	0	HOMO(A)->L+1(A) (24%), HOMO(A)->L+3(A) (24%), HOMO(B)->L+1(B) (24%), HOMO(B)->L+3(B) (24%)
12	18930.64	528.2442	0.0083	HOMO(A)->L+1(A) (25%), HOMO(B)->L+1(B) (25%)
13	19158.09	521.9728	0.1293	H-1(A)->L+1(A) (14%), H-1(B)->L+1(B) (14%)
14	19757.36	506.1406	1.1367	H-2(A)->LUMO(A) (25%), H-2(B)->LUMO(B) (25%)
15	20834.91	479.9636	0.0045	H-2(A)->LUMO(A) (26%), H-2(B)->LUMO(B) (26%)
16	21242.22	470.7605	0.6596	H-3(A)->LUMO(A) (25%), H-3(B)->LUMO(B) (25%)
17	21511.61	464.8652	0.0033	H-3(A)->L+1(A) (12%), H-3(B)->L+1(B) (12%)
18	21920.54	456.1932	0.0457	H-3(A)->L+1(A) (9%), H-3(B)->L+1(B) (9%)
19	22129.43	451.8868	0.0126	H-1(A)->L+2(A) (14%), H-1(B)->L+2(B) (14%)
20	22224.61	449.9517	0	H-1(A)->L+2(A) (16%), H-1(B)->L+2(B) (16%)
21	22410.92	446.211	0.0275	H-1(A)->L+3(A) (26%), H-1(B)->L+3(B) (26%)
22	22570.62	443.0539	0.0261	H-1(A)->L+3(A) (20%), H-1(B)->L+3(B) (20%)
23	22585.94	442.7533	0	H-1(A)->L+4(A) (11%), HOMO(A)->L+5(A) (11%), H-1(B)- >L+4(B) (11%), HOMO(B)->L+5(B) (11%)
24	22713.38	440.2691	0.0353	H-1(A)->L+4(A) (12%), H-1(B)->L+4(B) (12%),
25	24283.74	411.7982	0.0045	HOMO(A)->L+4(A) (23%), HOMO(B)->L+4(B) (23%)
26	24377.3	410.2177	0	H-1(A)->L+2(A) (30%), H-1(B)->L+2(B) (30%)
27	24405.53	409.7432	0.0006	HOMO(A)->L+4(A) (22%), HOMO(B)->L+4(B) (22%)
28	24542.64	407.4541	0.0075	H-1(A)->L+2(A) (33%), H-1(B)->L+2(B) (33%)
29	24693.47	404.9654	0.0338	H-2(A)->L+1(A) (12%), H-2(B)->L+1(B) (12%)
30	25147.56	397.6529	0.5684	H-2(A)->L+1(A) (11%), H-2(B)->L+1(B) (11%)
31	25415.34	393.4632	0.1257	H-6(A)->LUMO(A) (26%), H-6(B)->LUMO(B) (26%)
32	25467.76	392.6533	0.5918	H-6(A)->LUMO(A) (18%), H-6(B)->LUMO(B) (18%)
33	25511.32	391.9829	0	H-7(A)->LUMO(A) (16%), H-7(B)->LUMO(B) (16%)
34	25512.12	391.9705	0.0056	H-7(A)->LUMO(A) (16%), H-7(B)->LUMO(B) (16%)
35	26140.43	382.5492	0.0227	H-4(A)->LUMO(A) (25%), H-4(B)->LUMO(B) (25%)

Table E4.3 Summary of the TDDFT calculation of [La(CNTPP)₂]³⁻ (T). (solvent = DMSO).

No.	Energy (cm ⁻¹)	Wavelength (nm)	Osc. Strength	Major contribution
1	6930.722	1442.851	0.0091	H-1(B)->LUMO(B) (51%), HOMO(B)->L+1(B) (49%)
2	7746.149	1290.964	0.3108	H-1(B)->L+1(B) (41%), HOMO(B)->LUMO(B) (56%)
3	10364.22	964.8575	0.0116	HOMO(A)->L+1(A) (21%), H-1(B)->L+2(B) (27%)
4	10415.84	960.0758	0.1354	H-1(B)->L+3(B) (20%), HOMO(B)->L+2(B) (32%)
5	10788.47	926.9153	0	H-1(A)->L+2(A) (28%), HOMO(A)->LUMO(A) (55%)
6	10812.67	924.8411	0.0004	H-1(A)->LUMO(A) (52%), HOMO(A)->L+2(A) (30%)
7	12849.22	778.2574	0.0172	H-1(B)->LUMO(B) (34%), HOMO(B)->L+1(B) (33%)
8	13266.21	753.7949	0.0076	H-1(B)->L+1(B) (41%), HOMO(B)->LUMO(B) (30%)
9	14470.39	691.0662	0.0135	HOMO(A)->L+1(A) (18%), H-2(B)->LUMO(B) (24%)
10	14939	669.3888	0.0208	H-3(B)->LUMO(B) (19%), H-2(B)->L+1(B) (24%)
11	19223.42	520.1988	0.0146	H-1(A)->LUMO(A) (40%), HOMO(A)->L+2(A) (54%)
12	19237.94	519.8063	0.1081	HOMO(A)->L+1(A) (26%), H-2(B)->LUMO(B) (28%)
13	19353.27	516.7085	0	H-1(A)->L+2(A) (57%), HOMO(A)->LUMO(A) (38%)
14	20071.91	498.2086	1.3775	H-1(A)->L+1(A) (29%), HOMO(B)->L+2(B) (29%)
15	20694.57	483.2185	0.0032	H-1(A)->L+1(A) (26%), HOMO(A)->L+3(A) (24%)
16	21087.37	474.2176	0.0008	H-1(A)->L+3(A) (58%), HOMO(A)->L+1(A) (28%)
17	21334.17	468.7316	0.4377	HOMO(A)->L+3(A) (42%), H-1(B)->L+3(B) (15%)
18	21393.05	467.4415	0.0631	H-1(B)->L+2(B) (15%), HOMO(B)->L+3(B) (37%)
19	22252.84	449.3809	0.0211	H-3(B)->LUMO(B) (31%), H-1(B)->L+3(B) (20%)
20	22411.73	446.195	0	H-1(B)->L+4(B) (30%), HOMO(B)->L+5(B) (12%)
21	22472.22	444.9939	0.0341	HOMO(A)->L+4(A) (17%), HOMO(B)->L+4(B) (17%)
22	22552.07	443.4183	0.0006	H-3(B)->L+1(B) (21%), HOMO(B)->L+3(B) (20%)
23	22556.91	443.3232	0.0027	H-1(B)->L+5(B) (22%), HOMO(B)->L+4(B) (29%)
24	22685.96	440.8013	0	H-1(A)->L+4(A) (13%), HOMO(B)->L+5(B) (15%)
25	22922.28	436.2568	0	H-3(B)->L+1(B) (40%), H-2(B)->LUMO(B) (23%)
26	23187.63	431.2644	0.0028	H-3(B)->LUMO(B) (24%), H-2(B)->L+1(B) (17%)
27	24442.63	409.1212	0.0267	H-3(A)->L+2(A) (14%), H-2(A)->LUMO(A) (46%),
28	25324.2	394.8793	0.0954	H-8(B)->LUMO(B) (25%), H-5(B)->L+1(B) (26%)
29	25384.69	393.9383	0.1063	H-8(B)->L+1(B) (29%), H-5(B)->LUMO(B) (32%)
30	25466.96	392.6657	0.003	H-7(B)->L+1(B) (17%)
31	25481.47	392.442	0	H-9(B)->L+1(B) (16%), H-7(B)->LUMO(B) (17%)
32	25488.73	392.3302	1.2758	H-3(A)->LUMO(A) (37%), H-1(B)->L+3(B) (18%)
33	26261.41	380.7868	0.0011	H-8(A)->LUMO(A) (16%), H-4(B)->L+2(B) (16%)
34	26487.25	377.5402	0	H-2(A)->L+1(A) (12%)
35	26518.7	377.0923	0.0022	H-1(A)->L+5(A) (6%), HOMO(A)->L+4(A) (9%)

4.5 References

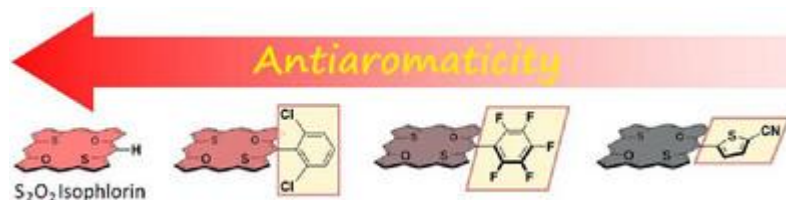
- [1] J. W. Buchler, D. K. P. Ng, in *The Porphyrin Handbook Vol. 3* (Ed.: K. Kadish, K. M. Smith, R. Guilard), Academic Press, San Diego, CA, **2000**, pp. 245–294.
- [2] J. Jiang, D. K. P. Ng, *Acc. Chem. Res.* **2009**, *42*, 79–88.
- [3] V. E. Pushkarev, L. G. Tomilova, V. N. Nemykin, *Coord. Chem. Rev.* **2016**, *319*, 110–179.
- [4] H. Wang, B.-W. Wang, Y. Bian, S. Gao, J. Jiang, *Coord. Chem. Rev.* **2016**, *306*, 195–216.
- [5] G.-Q. Jin, C. V. Chau, J. F. Arambula, S. Gao, J. L. Sessler, J.-L. Zhang, *Chem. Soc. Rev.* **2022**, *51*, 6177–6209.
- [6] J. W. Buchler, P. Hammerschmitt, I. Kaufeld, J. Löffler, *Chem. Ber.* **1991**, *124*, 2151–2159.
- [7] J. W. Buchler, B. Scharbert, *J. Am. Chem. Soc.* **1988**, *110*, 4272–4276.
- [8] J. K. Duchowski, D. F. Bocian, *J. Am. Chem. Soc.* **1990**, *112*, 3312–3318.
- [9] J. H. Perng, J. K. Duchowski, D. F. Bocian, *J. Phys. Chem.* **1991**, *95*, 1319–1323.
- [10] K. Yamashita, T. Yamanaka, N. Sakata, T. Ogawa, *Chem. Asian J.* **2018**, *13*, 1692–1698.
- [11] S. Takamatsu, T. Ishikawa, S.-Y. Koshihara, N. Ishikawa, *Inorg. Chem.* **2007**, *46*, 7250–7252.
- [12] M. Gonidec, E. S. Davies, J. McMaster, D. B. Amabilino, J. Veciana, *J. Am. Chem. Soc.* **2010**, *132*, 1756–1757.
- [13] Y. Horii, M. Damjanović, K. Katoh, M. Yamashita, *Dalton Trans.* **2021**, *50*, 9719–9724.
- [14] S. Takamatsu, N. Ishikawa, *Polyhedron* **2007**, *26*, 1859–1862.
- [15] M. Gonidec, I. Krivokapic, J. Vidal-Gancedo, E. S. Davies, J. McMaster, S. M. Gorun, J. Veciana, *Inorg. Chem.* **2013**, *52*, 4464–4471.
- [16] D. V. Konarev, S. S. Khasanov, M. S. Batov, A. G. Martynov, I. V. Nefedova, Y. G. Gorbunova, A. Otsuka, H. Yamochi, H. Kitagawa, R. N. Lyubovskaya, *Inorg. Chem.* **2019**, *58*, 5058–5068.
- [17] J. P. Collman, J. L. Kendall, J. L. Chen, T. A. Eberspacher, C. R. Moylan, *Inorg. Chem.* **1997**, *36*, 5603–5608.
- [18] K. E. Sekhosana, R. Nkhahle, T. Nyokong, *ChemistrySelect* **2018**, *3*, 6671–6682.
- [19] K. Tashiro, K. Konishi, T. Aida, *J. Am. Chem. Soc.* **2000**, *122*, 7921–7926.
- [20] J. W. Buchler, A. D. Cian, J. Fischer, P. Hammerschmitt, R. Weiss, *Chem. Ber.* **1991**, *124*, 1051–1058.
- [21] S. Lee, *J. Am. Chem. Soc.* **1988**, *110*, 8000–8006.
- [22] K. M. Kadish, G. Moninot, Y. Hu, D. Dubois, A. Ibnlfassi, J. M. Barbe, R. Guilard, *J. Am. Chem. Soc.* **1993**, *115*, 8153–8166.
- [23] X. Ke, P. Yadav, L. Cong, R. Kumar, M. Sankar, K. M. Kadish, *Inorg. Chem.* **2017**, *56*, 8527–8537.
- [24] H. Duval, V. Bulach, J. Fischer, R. Weiss, *Inorg. Chem.* **1999**, *38*, 5495–5501.
- [25] Y. Song, R. E. Haddad, S.-L. Jia, S. Hok, M. M. Olmstead, D. J. Nurco, N. E. Schore, J. Zhang, J.-G. Ma, K. M. Smith, S. Gazeau, J. Pécaut, J.-C. Marchon, C. J. Medforth, J. A. Shelnutt, *J. Am. Chem.*

Soc. **2005**, 127, 1179–1192.

- [26] M. Sankar, P. Bhyrappa, *Chem. Phys. Lett.* **2019**, 730, 643–648.
- [27] P. Bhyrappa, M. Sankar, B. Varghese, *Inorg. Chem.* **2006**, 45, 4136–4149.
- [28] P. Bhyrappa, C. Arunkumar, B. Varghese, *Inorg. Chem.* **2009**, 48, 3954–3965.
- [29] J. D. Megiatto Jr, A. Antoniuk-Pablant, B. D. Sherman, G. Kodis, M. Gervaldo, T. A. Moore, A. L. Moore, D. Gust, *Proc. Natl. Acad. Sci. U. S. A.* **2012**, 109, 15578–15583.
- [30] S. Pillai, J. Ravensbergen, A. Antoniuk-Pablant, B. D. Sherman, R. van Grondelle, R. N. Frese, T. A. Moore, D. Gust, A. L. Moore, J. T. M. Kennis, *Phys. Chem. Chem. Phys.* **2013**, 15, 4775–4784.
- [31] J. Ravensbergen, A. Antoniuk-Pablant, B. D. Sherman, G. Kodis, J. D. Megiatto Jr, D. D. Méndez-Hernández, R. N. Frese, R. van Grondelle, T. A. Moore, A. L. Moore, D. Gust, J. T. M. Kennis, *J. Phys. Chem. B* **2015**, 119, 12156–12163.
- [32] R. Kumar, N. Chaudhri, M. Sankar, *Dalton Trans.* **2015**, 44, 9149–9157.
- [33] K. Karunanithi, P. Bhyrappa, *Inorganica Chim. Acta* **2015**, 427, 41–51.
- [34] A. Antoniuk-Pablant, Y. Terazono, B. J. Brennan, B. D. Sherman, J. D. Megiatto, G. W. Brudvig, A. L. Moore, T. A. Moore, D. Gust, *J. Mater. Chem. A* **2016**, 4, 2976–2985.
- [35] H. J. Callot, *Tetrahedron Lett.* **1973**, 14, 4987–4990.
- [36] Y. Fang, P. Bhyrappa, Z. Ou, K. M. Kadish, *Chem. Eur. J.* **2014**, 20, 524–532.
- [37] K. Yamashita, K. Nakajima, Y. Honda, T. Ogawa, *Chem. Eur. J.* **2020**, 26, 3633–3640.
- [38] H. Sugimura, K. Nakajima, K. Yamashita, T. Ogawa, *Eur. J. Org. Chem.* **2022**, e202200747.
- [39] H. Sugimura, K. Nakajima, K. Yamashita, *Asian J. Org. Chem.* **2025**, 14, e202400550.
- [40] J. W. Buchler, A. De Cian, J. Fischer, M. Kihn-Botulinski, R. Weiss, *Inorg. Chem.* **1988**, 27, 339–345.
- [41] G. S. Girolami, P. A. Gorlin, S. N. Milam, K. S. Suslick, S. R. Wilson, *J. Coord. Chem.* **1994**, 32, 173–212.
- [42] M. Ikeda, M. Takeuchi, S. Shinkai, F. Tani, Y. Naruta, *Bull. Chem. Soc. Jpn.* **2001**, 74, 739–746.
- [43] M. M. Ayhan, A. Singh, C. Hirel, A. G. Gürek, V. Ahsen, E. Jeanneau, I. Ledoux-Rak, J. Zyss, C. Andraud, Y. Bretonnière, *J. Am. Chem. Soc.* **2012**, 134, 3655–3658.
- [44] A. L. Spek, *Acta Crystallogr. C Struct. Chem.* **2015**, 71, 9–18.
- [45] A. G. De Crisci, V. T. Annibale, G. K. Hamer, A. J. Lough, U. Fekl, *Dalton Trans.* **2010**, 39, 2888–2902.

Chapter 5.

Tuning Antiaromaticity Through *Meso*-Substituent Orientation in Core-Modified Isophlorins



Abstract: Antiaromaticity is an essential principle in organic chemistry that significantly influences the properties of cyclic π -conjugated systems. This study systematically investigated the effects of *meso*-substituents on the antiaromaticity of dithiadioxaisophlorins (S_2O_2Iphs), which are stable isophlorin derivatives with strong antiaromatic characteristics. In previous research involving the synthesis of three S_2O_2Iph derivatives—one with a 3,5-bis(trifluoromethyl)phenyl substituent and the other with a 5-cyanothien-2-yl substituent and the other with — 1H NMR measurements indicated a significant difference in the strength of antiaromaticity between the two compounds. In this chapter, a comprehensive analysis employing various computational methods (including NICS, GIMIC, HOMA/HOMAc, and AV1245/ AV_{min}) showed that the steric bulkiness of the substituent primarily determines the inclination angle relative to the isophlorin macrocycle, which in turn significantly influences the degree of antiaromaticity. Bulkier substituents maintain larger tilt angles, preserving stronger antiaromaticity, while less bulky groups allow greater π -conjugation with the macrocycle, thereby reducing antiaromaticity. These findings provide valuable guidance for the design of functional antiaromatic materials with tunable electronic properties.

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5.1 Introduction

Aromaticity and antiaromaticity are fundamental concepts in organic chemistry that significantly influence the properties of cyclic π -conjugated systems.^[1–3] While aromatic compounds following Hückel's $(4n+2)\pi$ -electron rule are well-studied due to their stability, antiaromatic compounds with $4n\pi$ -electrons remain rare due to their inherent instability. However, understanding antiaromaticity is crucial not only for fundamental chemistry, but also because antiaromatic compounds exhibit unique electronic properties that make them promising candidates for organic electronic materials and optoelectronic devices.^[4–13]

Recent advances in synthesis have enabled the preparation of increasingly stable antiaromatic systems, renewing interest in their properties, and applications. Among these, porphyrinoid-based antiaromatic molecules,^[14–16] particularly isophlorins (two electron-reduced porphyrins),^[17,18] have emerged as valuable platforms for investigating antiaromaticity. Core-modified isophlorins, where heteroatoms, such as oxygen and sulfur replace pyrrole nitrogen atoms, offer opportunities to modulate their electronic structure and stability.^[19,20] The properties of antiaromatic compounds can be tuned through various structural modifications. Recent studies have revealed that substituents influence their electronic structure, stability, and assembly behavior. Among antiaromatic porphyrinoids, norcorrole derivatives are extensively studied with various aryl and alkyl substituents at *meso*-positions.^[21–29] However, the relationship between substituent effects and antiaromaticity has not yet been systematically discussed in these compounds.

Several studies have provided important insights into substituent effects on antiaromatic systems. Takase and coworkers demonstrated that the electronic properties of π -extended antiaromatic systems can be systematically controlled by altering the structural relationship between substituents and the macrocycle.^[29] Salikov and coworkers showed that the antiaromaticity of cycloheptatrienyl anions is primarily determined by the geometry of the anion, which in turn is controlled by the substituent properties.^[30] More recently, Shimizu and coworkers reported that *meso*-substituents of 5,15-dioxaporphyrins affect their crystal packing and oxidation behavior, although the antiaromaticity itself was relatively unchanged in their system.^[31] Chapter 2 and 3 demonstrated that introducing electron-withdrawing cyano groups at the β -positions of isophlorins significantly enhanced their stability while reducing antiaromaticity due to π -conjugation effects.^[32,33] These studies suggest that the relationship between substituents and antiaromaticity vary significantly depending on the molecular framework and position of substitution.

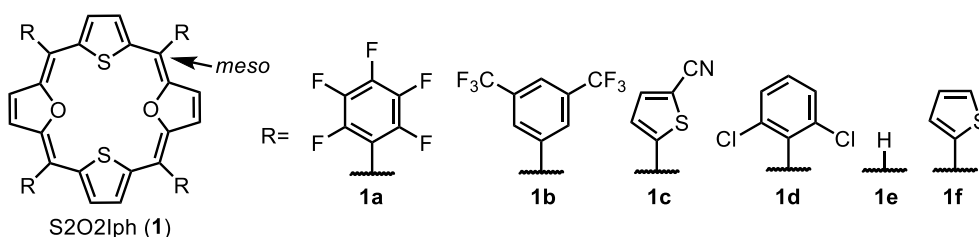


Figure 5.1 Structure of S₂O₂Iphs (**1**).

In this chapter, systematic investigation of the *meso*-substituents effects on dithiadioxaisophlorins (S₂O₂Iphs, **1**; Figure 5.1) is reported, which are attainable stable isophlorin derivatives with strong antiaromatic characteristics.^[17,18,20] Pentafluorophenyl-substituted S₂O₂Iph (**1a**) was reported by Anand et al.,^[20] 3,5-Bis(trifluoromethyl)phenyl-substituted S₂O₂Iph (**1b**) was reported by Honda et al.,^[34] and 5-cyanothien-2-yl-substituted S₂O₂Iph (**1c**) was reported by Isoda et al.^[35] The strength of antiaromaticity was estimated to be **1a** = **1b** > **1c** by ¹H NMR. In this chapter, quantum chemical calculations were performed to investigate the strength of antiaromaticity in these isophlorin analogues in detail. By examining the substituent effects on antiaromaticity, the author aims to establish design guidelines for future antiaromatic compounds.

5.2 Results and Discussion

5.2.1 Theoretical Calculations—Structural Comparison

The geometry-optimized structures of S₂O₂Iphs (**1a–1c**) were obtained at the cam-B3LYP/6-311G(d,p) theory level, and are shown in Figure 5.2a–c exhibiting saddle-type distorted structures. Figure 5.2e–g shows the skeletal deviations of the macrocycle atoms from the mean plane defined by the 24 core atoms. The analysis revealed decreasing planarity (**1a** > **1b** > **1c**) with the thiophene rings showing larger deviations from the mean plane than the furan rings in all compounds. The mean plane deviation (mpd), which serves as an index of planarity, followed the order **1a** (0.223) < **1b** (0.303) < **1c** (0.354). The tilt angles between the *meso*-substituents and the mean plane of the isophlorin macrocycles decreased (**1a** (63.0°) > **1b** (52.1°) > **1c** (51.7°)) correlating with the steric bulkiness of the substituents and mpd values.

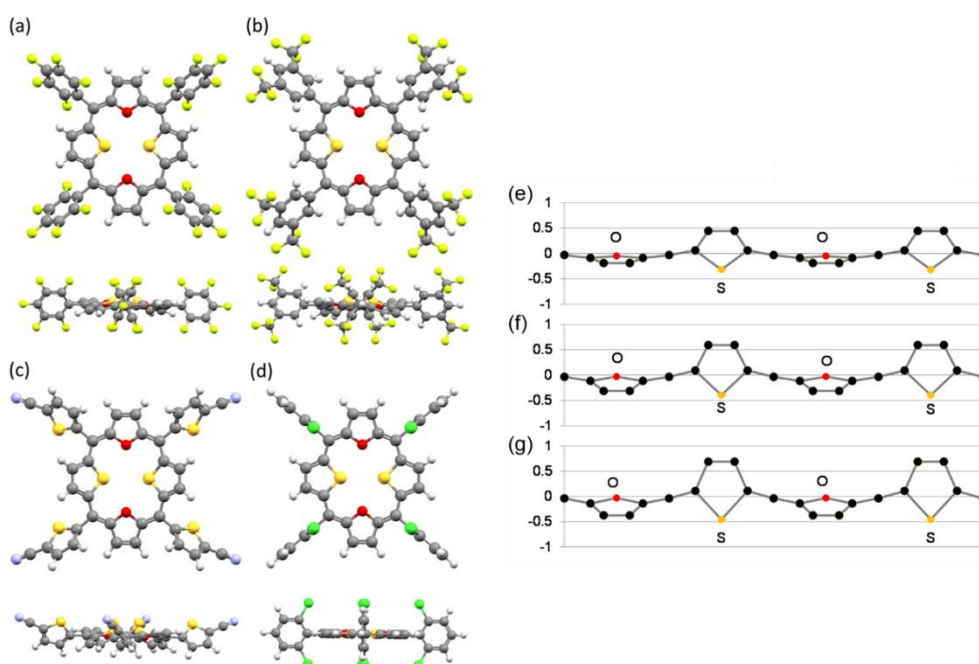


Figure 5.2 (a) Information for geometry optimized structures. Top and side views of (a) **1a**, (b) **1b**, (c) **1c**, and (d) **1d**. Skeletal deviations (Å) of the macrocycle atoms from the 24-plane for the geometry-optimized structures of (e) **1a**, (f) **1b**, and (g) **1c**.

Notably, Valiev et al. also performed computational studies on compounds equivalent to **1a** and the *meso*-free analog **1e** in their investigation of the magnetically induced current pathways and optical properties of isophlorins.^[37] However, their **1a** optimized structure exhibited imaginary frequencies related to the rotations of the C₆F₅ groups and was completely planar with the aryl groups positioned orthogonally to the isophlorin plane. In contrast, in this Chapter, **1a** optimized structure represents a true energy minimum without imaginary frequencies, suggesting that the calculated nonplanar saddle-shaped conformation is more reliable. To verify this, geometry optimizations of four conformers of **1a** was performed at the same computational level, including the reported saddle conformer (*C*_{2v}) and the completely planar (*D*_{2h}) conformer, similar to the model of Valiev et al. An energy comparison confirmed that the saddle structure was more stable (Figure 5.3). The energy difference between this structure and the planar conformer without imaginary frequencies (*D*₂) was remarkably small (0.58 kcal mol⁻¹).

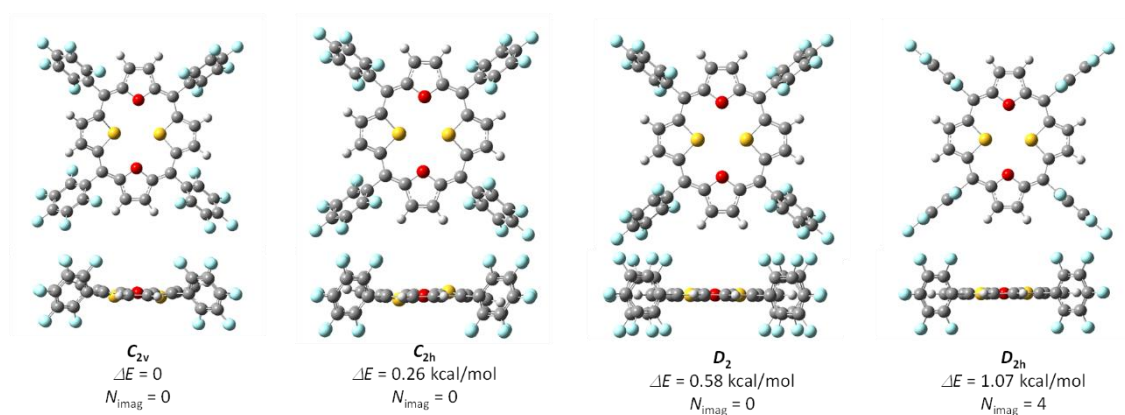


Figure 5.3 Comparison of the relative energy for the conformer of **1a**. N_{imag} means the number of imaginal frequencies.

To further investigate the effect of *meso*-substituents on planarity, geometry optimizations were performed for **1d** and its *meso*-free analog **1e**. Unlike **1a–1c**, **1d** and **1e** exhibited perfectly planar structures with zero mpd. This demonstrates that aryl substituents at the *meso*-positions reduce the planarity of isophlorins thus decreasing their antiaromaticity. The degree of planarity depends on substituent bulkiness, with the sterically demanding 2,6-dichlorophenyl groups in **1d** adopting an orthogonal orientation relative to the isophlorin macrocycle, thus minimizing their effect on planarity. For the unsubstituted isophlorin (**1e**), both the calculations and those of Valiev et al.^[37] showed a completely planar structure without imaginary frequencies.

To investigate the influence of the cyano groups on the thiophene rings introduced for the stabilization of isophlorin **1c**, the structure of derivative **1f** without cyano groups was also performed. The mpd of **1f** was 0.294, indicating higher planarity (lower mpd) than **1c**. Additionally, the tilt angle of the substituents was larger (57.6°) than that of **1c**. These results demonstrate that the cyano groups on the thiophene rings significantly affect the structure of the isophlorin ring.

5.2.2 Theoretical Calculations—Electronic Structure Analysis

The steric bulkiness of substituents significantly influences the tilt angle relative to the isophlorin plane. Smaller tilt angles enhance π -electron perturbation between the isophlorin and aryl substituents, potentially reducing antiaromaticity through contributions from nonaromatic resonance structures. Molecular orbital (MO) analysis revealed that **1c**, with its smaller tilt angle, exhibited delocalized molecular orbitals extending across the molecule with more extensive π -conjugation toward the *meso*-substituents (Figures 5.4, and E19-E21). In contrast, compounds with larger tilt angles showed more localized π -conjugation. This computationally predicted extension of π -conjugation in **1c** is further corroborated by the observed bathochromic shifts and spectral broadening in its absorption spectrum.

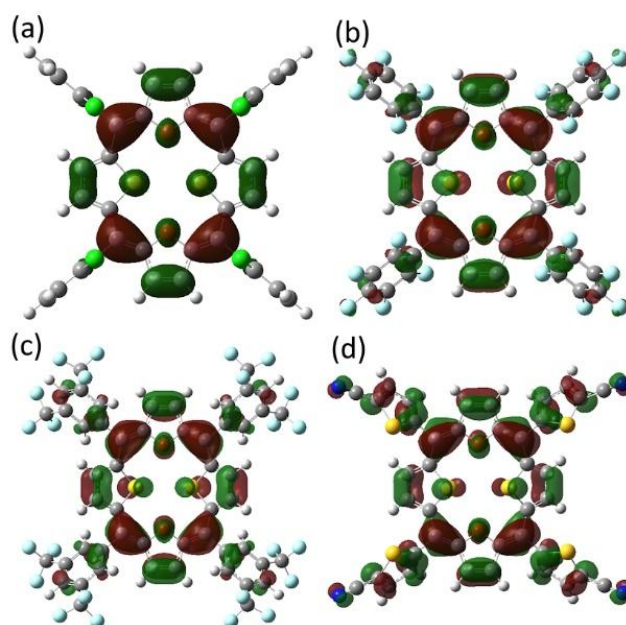


Figure 5.4 HOMO-1 of (a) **1d**, (b) **1a**, (c) **1b**, and (d) **1c**.

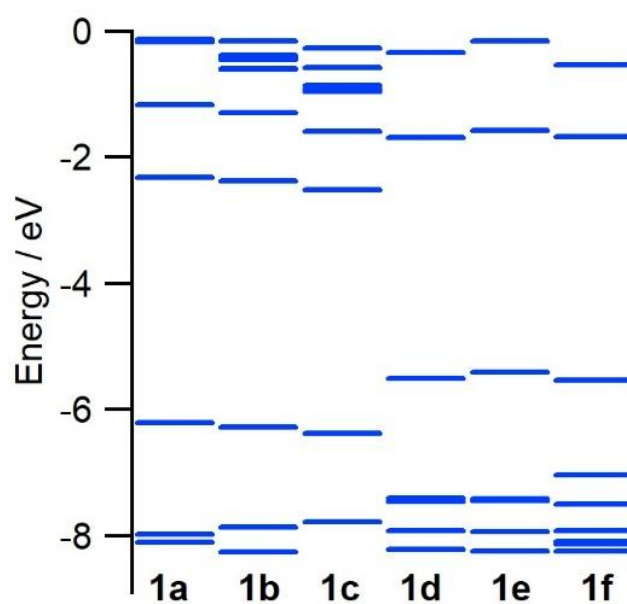


Figure 5.3 MO energy diagram of **S₂O₂Iph 1**.

The MO energy diagrams of **1a–f** (Figure 5.5) show that the HOMO energies (ca. -6 eV) of **1d–f** were substantially higher than those of the isolated compounds **1a–c**. This explains the instability of **1d–f** toward oxidation and highlights the importance of electron-withdrawing substituents in stabilizing isophlorins.

5.2.3 Evaluation of Antiaromaticity by Calculations

To quantitatively assess the antiaromaticity of S₂O₂Iphs, multiple computational approaches were employed, based on magnetic, geometric, and electronic criteria. These complementary methods provided a comprehensive understanding of the antiaromatic characteristics of series of compounds in this Chapter (Table 5.1). Nucleus-independent chemical shift (NICS)^[36,37] calculations were performed based on the optimized structures at the center of the macrocycle. The NICS values, which measure the magnetic shielding at the center of the aromatic/antiaromatic ring (positive values indicating stronger antiaromaticity), revealed that the antiaromaticity strength decreased (**1e** > **1d** > **1a** > **1b** ≈ **1f** > **1c**), correlating with the magnitude of the tilt angle between the *meso*-substituents and isophlorin macrocycles. Notably, **1d** and **1e** exhibited pronounced antiaromaticity, which is attributed to their completely planar isophlorin macrocycles.

To further validate these findings, the magnetically induced current densities were calculated using the program GIMIC.^[38,39] The induced current density values followed the same trend as the NICS results: **1e** (21 nA T⁻¹) > **1d** (20 nA T⁻¹) > **1a** (16 nA T⁻¹) > **1b** (14 nA T⁻¹) > **1c** (12 nA T⁻¹), supporting the magnetic-based assessment of antiaromaticity. Notably, Valiev et al. also performed GIMIC calculations for compounds equivalent to **1a** and **1e** and reported a reduction in the paratropic ring current strength of **1a** compared to that of **1e**.^[36,41] However, the calculations indicate a more pronounced decrease in antiaromaticity owing to the presence of *meso*-substituents. This difference is attributed to the aforementioned structural discrepancies.

Table 5.1 Antiaromatic indices for S₂O₂Iphs.

	NICS(0) ^[a]	NICS(1) ^[a]	GIMIC / nA T ⁻¹ [b]	mpd / Å	HOMA	HOMAc	AV1245	AV _{min}
1a	11 (46)	11 (38)	16	0.223	0.433	0.676	1.12	0.80
1b	9 (41)	9 (34)	14	0.303	0.426	0.673	1.12	0.74
1c	8 (37)	8 (31)	12	0.354	0.430	0.676	1.10	0.72
1d	14 (56)	13 (44)	20	0	0.445	0.683	1.14	0.84
1e	16 (59)	14 (47)	21	0	0.473	0.698	1.25	0.92
1f	9 (41)	9 (35)	ND ^[c]	0.294	0.434	0.678	1.12	0.76

[a] NICS_{iso} values calculated at cam-B3LYP/6-311+G(2d,p)//cam-B3LYP/6-311G(d,p) Values in parentheses are NICS_{zz} values. [b] Integrated current strengths passing through C_{meso}–C_a bonds. [c] No data.

To complement the magnetic criteria, geometry-based aromatic/antiaromatic indices was also investigated, including the harmonic oscillator model of aromaticity (HOMA)^[42,43] and its

improved version, HOMAc, considering both aromatic and antiaromatic compounds.^[44] These indices provide insights into the bond length alternation patterns that are characteristic of aromatic and antiaromatic systems. For the calculations in this Chapter, the ring was considered as encompassing all 24 carbon atoms of the isophlorin skeleton, as this was the most relevant conjugation pathway by comparison with other pathways (for **1e**, Figure 5.6) and localized orbital locator of π orbitals (LOL- π) analysis (Figure 5.7), which visualized π -electron localization and delocalization within the molecule.^[45]

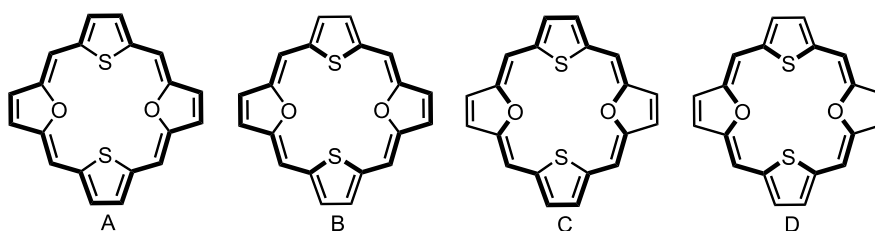


Figure 5.6 HOMA values for various conjugation pathways in **1e**. Note that HOMAc values could not be calculated for the conjugation pathways B and D because the parameters for C–S bonds in these specific arrangements have not yet been defined.^[45]

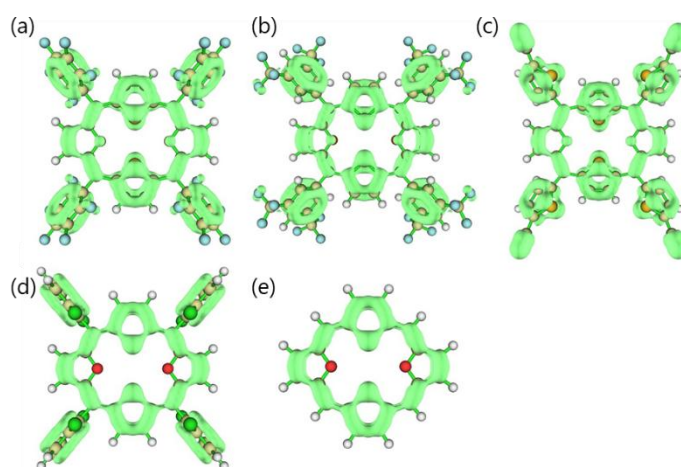


Figure 5.7 LOL- π (localized orbital locator of π orbitals) isosurfaces (isovalue: 0.42 a.u.) of (a) **1a**, (b) **1b**, (c) **1c**, (d) **1d**, and (e) **1e**.

The HOMA values followed the order: **1e** (0.473) > **1d** (0.445) > **1f** (0.434) > **1a** (0.433) > **1c** (0.430) > **1b** (0.426). The HOMAc values were higher than the original HOMA values but maintained the same relative order. These geometric indices aligned with the magnetic indicators, with slight deviations in the relative positions of **1b** and **1c**. This minor discrepancy may reflect the influence of extended π -conjugation with substituents in **1c**, which affects bond length alternation patterns while having less impact on magnetic properties.

Finally, electronic aromaticity indices were evaluated,^[46] specifically AV1245^[47] and AV_{min},^[48] which were developed for assessing antiaromaticity in large cyclic π -conjugated systems such as porphyrinoids.^[48,49] Recent studies have suggested AV_{min} as the most reliable electronic indicator for antiaromaticity.^[48,49] Both indices identified **1e** and **1c** as having the highest and lowest antiaromaticity, respectively, which is consistent with the conclusions based on other indicators. The AV_{min} values, in particular, showed perfect agreement with the order established by the NICS and GIMIC calculations. The AV1245 values were also in agreement, except for those of compounds **1a**, **1b**, and **1f**, which had similar values.

Based on this comprehensive analysis integrating experimental ¹H NMR data, structural planarity measurements, and multiple computational indicators (NICS, GIMIC, HOMA/HOMAc, and AV1245/AV_{min}), the antiaromatic character of these systems decreases in the order **1e** > **1d** > **1a** > **1b** ($\approx$ **1f**) > **1c**. This trend consistently demonstrates the significant influence of *meso*-substituents on the antiaromaticity of isophlorins, primarily through their effect on macrocycle planarity and the extent of π -conjugation.

5.3 Summary

This study systematically investigated the effect of *meso*-substituents on the antiaromaticity of S₂O₂Iphs. Through a comprehensive analysis integrating multiple computational approaches (NICS, GIMIC, HOMA/HOMAc, and AV1245/AV_{min}), the steric demands of *meso*-substituents critically influence antiaromaticity through their effect on the tilt angle between the substituents and the isophlorin macrocycle. The antiaromatic character of S₂O₂Iphs decreased in the order **1e** > **1d** > **1a** > **1b** > **1c**, directly correlating with the structural changes driven by the substituent bulk. Unsubstituted (**1e**) and orthogonally substituted (**1d**) isophlorins maintained completely planar macrocycles with strong antiaromaticity. As the tilt angle decreased from **1a** to **1c** due to decreasing steric hindrance, the extent of π -conjugation between the substituents and the macrocycle increased, leading to weaker antiaromaticity. The findings in this Chapter highlight the dual requirements for stable antiaromatic systems: electron-withdrawing groups are necessary to lower the HOMO energies and prevent oxidation, whereas their steric bulk influences the degree of antiaromaticity preservation.

This research provides a clear structure-property relationship that guides the rational design of functional antiaromatic materials with tunable electronic properties. 2,6-Dichlorophenyl derivative (**1d**), which combines strong antiaromaticity with sufficient stability, these results revealed strategies for balancing these competing properties. These insights contribute to the growing field of antiaromatic material design for potential applications in organic electronics and optoelectronic devices. Future work will focus on developing isophlorin derivatives that maintain strong antiaromaticity through appropriate substituent orientation while achieving sufficient stability through electron-withdrawing effects without compromising macrocycle planarity.

5.4 Experimental Section

5.4.1 DFT Calculations

Geometries of all models were optimized by the DFT method at the cam-B3LYP/6-311G(d,p) level. For the coordinates of the optimized structure, see pp. 9–26 (in <https://aces.onlinelibrary.wiley.com/action/downloadSupplement?doi=10.1002%2Fajoc.202500372&file=ajoc70002-sup-0001-SupMat.pdf>). To confirm that the optimized geometries were not in the saddle but stable points, frequency calculations were performed.

Nucleus-independent chemical shifts (NICS) values were calculated at the GIAO-cam-B3LYP/6-311+G(2d,p) level using geometry-optimized structures. Magnetically induced current densities were calculated using the GIMIC program^[39,50] based on the optimized structure. The NMR shielding constants were calculated using gauge-including atomic orbitals (GIAO) at cam-B3LYP/6-311+G(2d,p) level. The integration of the current density through a bond (nA T^{-1}) was performed using a rectangular plane perpendicular to the plane of the macrocycle. The rectangular plane had dimensions of 10 bohr ($5.2 \text{ \AA}$) high 4.4 bohr ($2.3 \text{ \AA}$) wide and spanned the center of the bond of interest. The magnetic field was placed perpendicular to the plane of the macrocycle. Electronic indices of aromaticity ($\text{AV1245}^{[47]}$ and $\text{AV}_{\text{min}}^{[53]}$) were calculated with the AIMAll^[54,55] and ESI-3D^[54,55] program packages.

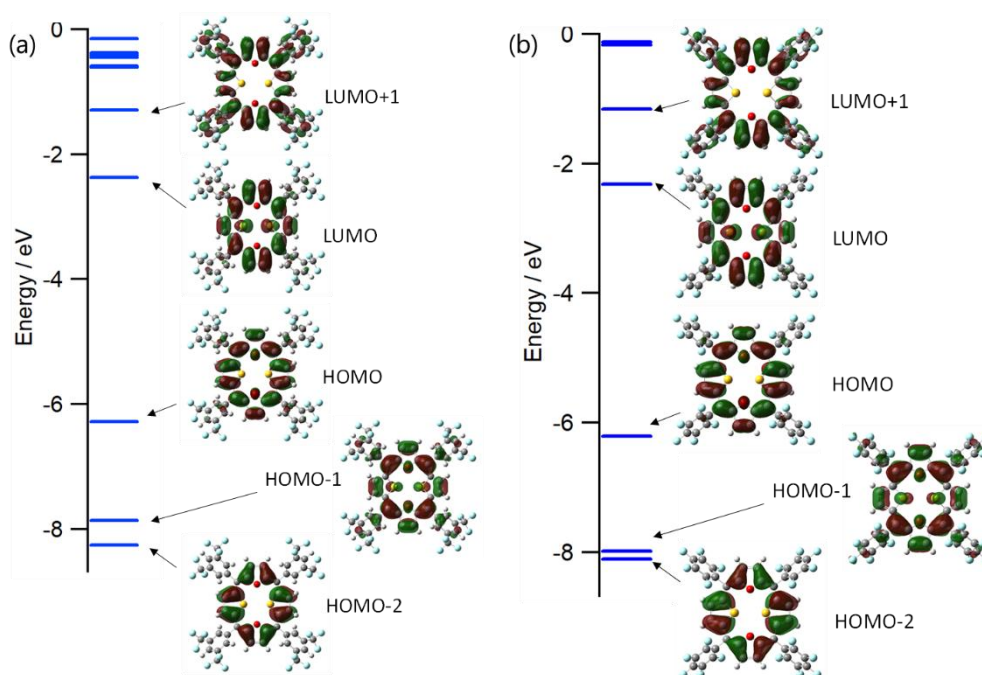


Figure E5.1 Frontier orbital energy diagram and frontier orbitals of (a) **1a** and (b) **1b**.

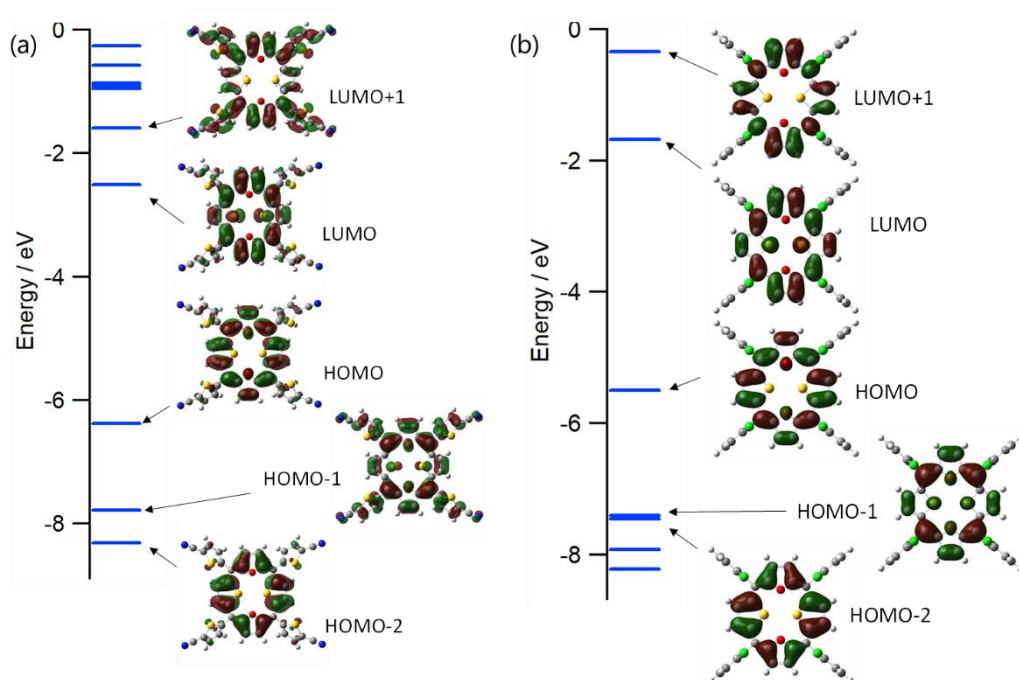


Figure E5.2 Frontier orbital energy diagram and frontier orbitals of (a) **1c** and (b) **1d**.

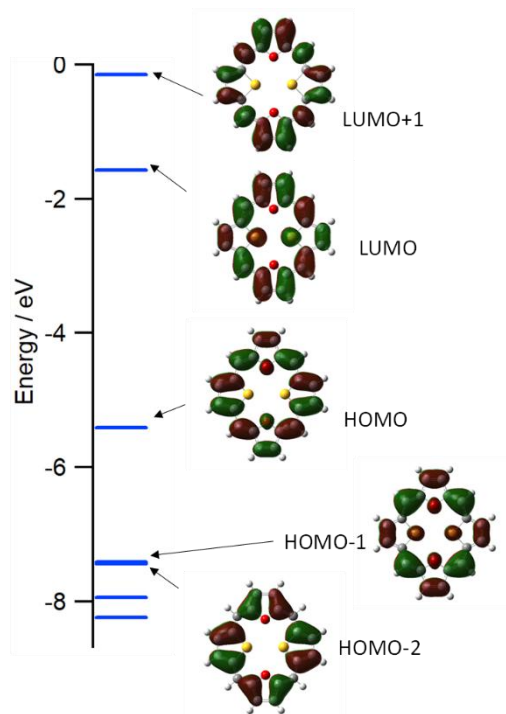


Figure E5.3 Frontier orbital energy diagram and frontier orbitals of **1e**.

5.5 References

- [1] R. Breslow, *Acc. Chem. Res.* **1973**, *6*, 393–398.
- [2] R. Gleiter, G. Haberhauser, *Aromaticity and Other Conjugation Effect*, Wiley-VCH, Weinheim, Germany, **2012**.
- [3] I. Fernández, Ed. , *Aromaticity: Modern Computational Methods and Applications*, Elsevier, **2021**.
- [4] J.-Y. Shin, T. Yamada, H. Yoshikawa, K. Awaga, H. Shinokubo, *Angew. Chem. Weinheim Bergstr. Ger.* **2014**, *126*, 3160–3165.
- [5] S. Fujii, S. Marqués-González, J.-Y. Shin, H. Shinokubo, T. Masuda, T. Nishino, N. P. Arasu, H. Vázquez, M. Kiguchi, *Nat. Commun.* **2017**, *8*, 15984.
- [6] T. Stuyver, M. Perrin, P. Geerlings, F. De Proft, M. Alonso, *J. Am. Chem. Soc.* **2018**, *140*, 1313–1326.
- [7] C. Hong, J. Baltazar, J. D. Tovar, *European J. Org. Chem.* **2022**, 2022, DOI 10.1002/ejoc.202101343.
- [8] J. Wu, Y. Chen, J. Liu, Z. Pang, G. Li, Z. Lu, Y. Huang, A. Facchetti, T. J. Marks, *J. Mater. Chem. C Mater. Opt. Electron. Devices* **2022**, *10*, 2724–2731.
- [9] X.-L. Zheng, H.-S. Lin, B.-W. Zhang, S. Maruyama, Y. Matsuo, *J. Org. Chem.* **2022**, *87*, 5457–5463.
- [10] R. Santiago, M. À. Carvajal, J. Poater, I. de P. R. Moreira, S. T. Bromley, M. Deumal, J. Ribas-Ariño, *Chem. Sci.* **2024**, *16*, 430–447.
- [11] J. Sprachmann, T. Wachsmuth, M. Bhosale, D. Burmeister, G. J. Smales, M. Schmidt, Z. Kochovski, N. Grabicki, R. Wessling, E. J. W. List-Kratochvil, B. Esser, O. Dumele, *J. Am. Chem. Soc.* **2023**, *145*, 2840–2851.
- [12] W. E. Meador, M. A. Saucier, M. R. Tucker, N. A. Kruse, A. J. Mobley, C. R. Brower, S. R. Parkin, K. M. Clark, N. I. Hammer, G. S. Tschumper, J. H. Delcamp, *Chem. Sci.* **2024**, *15*, 12349–12360.
- [13] R. Lavendomme, M. Yamashina, *Chem. Sci.* **2024**, *15*, 18677–18697.
- [14] J. L. Sessler, D. Seidel, *Angew. Chem. Int. Ed Engl.* **2003**, *42*, 5134–5175.
- [15] S. Saito, A. Osuka, *Angew. Chem. Int. Ed.* **2011**, *50*, 4342–4373.
- [16] A. Osuka, S. Saito, *Chem. Commun.* **2011**, *47*, 4330.
- [17] B. K. Reddy, A. Basavarajappa, M. D. Ambhore, V. G. Anand, *Chem. Rev.* **2017**, *117*, 3420–3443.
- [18] P. Pushpanandan, M. Ravikanth, *Chem. Rec.* **2022**, *22*, e202200144.
- [19] R. Bachmann, F. Gerson, G. Gescheidt, E. Vogel, *J. Am. Chem. Soc.* **1992**, *114*, 10855–10860.
- [20] J. S. Reddy, V. G. Anand, *J. Am. Chem. Soc.* **2008**, *130*, 3718–3719.
- [21] T. Ito, Y. Hayashi, S. Shimizu, J.-Y. Shin, N. Kobayashi, H. Shinokubo, *Angew. Chem. Int. Ed.* **2012**, *51*, 8542–8545.
- [22] R. Nozawa, K. Yamamoto, J.-Y. Shin, S. Hiroto, H. Shinokubo, *Angew. Chem. Int. Ed Engl.* **2015**,

54, 8454–8457.

- [23] T. Yoshida, D. Sakamaki, S. Seki, H. Shinokubo, *Chem. Commun. (Camb.)* **2017**, 53, 1112–1115.
- [24] S. Ukai, A. Takamatsu, M. Nobuoka, Y. Tsutsui, N. Fukui, S. Ogi, S. Seki, S. Yamaguchi, H. Shinokubo, *Angew. Chem. Weinheim Bergstr. Ger.* **2022**, 134, DOI 10.1002/ange.202114230.
- [25] S. Itabuchi, R. Nozawa, T. Yoshida, N. Fukui, H. Shinokubo, *J. Porphyr. Phthalocyanines* **2022**, A-E.
- [26] S. Kino, S. Ukai, N. Fukui, R. Haruki, R. Kumai, Q. Wang, S. Horike, Q. M. Phung, D. Sundholm, H. Shinokubo, *J. Am. Chem. Soc.* **2024**, 146, 9311–9317.
- [27] S.-Y. Liu, S. Li, S. Ukai, R. Nozawa, N. Fukui, R. Sugimori, R. Kishi, H. Shinokubo, *Chem. Eur. J.* **2024**, 30, e202400292.
- [28] S. Ishikawa, K. Yamasumi, S. Sugiura, S. Sato, G. Watanabe, Y. H. Koo, S. Seki, Y. Bando, Y. Haketa, H. Shinokubo, H. Maeda, *Chem. Sci.* **2024**, 15, 7603–7609.
- [29] M. Takase, T. Takata, K. Oki, S. Mori, H. Uno, *Chem. Sci.* **2023**, 14, 7036–7043.
- [30] R. F. Salikov, A. Y. Belyy, M. K. Ilyushchenko, D. N. Platonov, A. D. Sokolova, Y. V. Tomilov, *Chem. Eur. J.* **2024**, 30, e202401041.
- [31] Y. Tanaka, T. Tsutsumi, S. Mori, Y. Ide, T. Ikeue, S. Shimizu, *Chem. Asian J.* **2025**, 20, e202401337.
- [32] H. Sugimura, K. Nakajima, K. Yamashita, T. Ogawa, *Eur. J. Org. Chem.* **2022**, e202200747.
- [33] H. Sugimura, K. Nakajima, K. Yamashita, *Asian J. Org. Chem.* **2025**, 14, e202400550.
- [34] K. Honda, 大阪大学大学院理学研究科修士論文 **2021**.
- [35] M. Isoda, H. Sugimura, Y. Honda, K.-I. Yamashita, *Asian J. Org. Chem.* **2025**, 14, DOI 10.1002/ajoc.202500372.
- [36] R. R. Valiev, H. Fliegl, D. Sundholm, *J. Phys. Chem. A* **2013**, 117, 9062–9068.
- [37] P. von R. Schleyer, C. Maerker, A. Dransfeld, H. Jiao, N. J. R. van Eikema Hommes, *J. Am. Chem. Soc.* **1996**, 118, 6317–6318.
- [38] Z. Chen, C. S. Wannere, C. Corminboeuf, R. Puchta, P. von R. Schleyer, *Chem. Rev.* **2005**, 105, 3842–3888.
- [39] J. Jusélius, D. Sundholm, J. Gauss, *J. Chem. Phys.* **2004**, 121, 3952–3963.
- [40] H. Fliegl, S. Taubert, O. Lehtonen, D. Sundholm, *Phys. Chem. Chem. Phys.* **2011**, 13, 20500–20518.
- [41] R. R. Valiev, H. Fliegl, D. Sundholm, *Phys. Chem. Chem. Phys.* **2017**, 19, 25979–25988.
- [42] J. Kruszewski, T. M. Krygowski, *Tetrahedron Lett.* **1972**, 13, 3839–3842.
- [43] T. M. Krygowski, H. Szatyłowicz, O. A. Stasyuk, J. Dominikowska, M. Palusiak, *Chem. Rev.* **2014**, 114, 6383–6422.
- [44] E. M. Arpa, S. Stafström, B. Durbeej, *J. Org. Chem.* **2025**, 90, 1297–1308.
- [45] H. L. Schmider, A. D. Becke, *Theochem* **2000**, 527, 51–61.

- [46] F. Feixas, E. Matito, J. Poater, M. Solà, *Chem. Soc. Rev.* **2015**, *44*, 6434–6451.
- [47] E. Matito, *Phys. Chem. Chem. Phys.* **2016**, *18*, 11839–11846.
- [48] I. Casademont-Reig, T. Woller, J. Contreras-García, M. Alonso, M. Torrent-Sucarrat, E. Matito, *Phys. Chem. Chem. Phys.* **2018**, *20*, 2787–2796.
- [49] E. Desmedt, I. Casademont-Reig, R. Monreal-Corona, F. De Vleeschouwer, M. Alonso, *Chem. Eur. J.* **2024**, *30*, e202401933.
- [50] D. Sundholm, H. Fliegl, R. J. F. Berger, *Wiley Interdiscip. Rev. Comput. Mol. Sci.* **2016**, *6*, 639–678.
- [51] C. García-Fernández, E. Sierda, M. Abadía, B. Bugenhagen, M. H. Prosenc, R. Wiesendanger, M. Bazarnik, J. E. Ortega, J. Brede, E. Matito, A. Arnau, *J. Phys. Chem. C* **2017**, *121*, 27118–27125.
- [52] I. Casademont-Reig, T. Woller, J. Contreras-García, M. Alonso, M. Torrent-Sucarrat, E. Matito, *Phys. Chem. Chem. Phys.* **2018**, *20*, 2787–2796.
- [53] T. A. Keith, *AIMAll (Version 19.10.12)*, TK Gristmill Software, Overland Park KS, USA, **2019**.
- [54] E. Matito, *ESi-3D: Electron Sharing Indexes Program for 3D Molecular Space Partitioning*, Institute Of Computational Chemistry And Catalysis, University Of Girona, Catalonia, Spain, **2015**.
- [55] E. Matito, M. Solà, P. Salvador, M. Duran, *Faraday Discuss.* **2007**, *135*, 325–345.

Chapter 6. Conclusion of This Thesis

This thesis contributes to the understanding of antiaromaticity from both experimental and computational perspectives through the synthesis of antiaromatic isophlorins, their metal complexes, and core-modified analogues.

In Chapter 1 the author provided the historical context and theoretical concepts of aromaticity and antiaromaticity, highlighting their synthesis and applications, particularly in porphyrinoids. It began with an overview of the discovery of aromatic and antiaromatic compounds. Next, electron counting rules were outlined to help determine whether a compound is aromatic or antiaromatic, and several descriptors were introduced to characterize the degree of aromaticity and antiaromaticity. Following a summary of experimental advancements in the study of representative antiaromatic compounds, the author introduced porphyrinoids, which are aromatic compounds commonly found in nature. Additionally, the author explored the unique structural features of porphyrinoids and included experimental studies on the antiaromatic porphyrinoid known as isophlorin.

In Chapter 2, the successful synthesis of antiaromatic isophlorins containing four nitrogen atoms was reported by introducing the electron-withdrawing substituent CN groups. This antiaromatic isophlorins remained stable in the solid state even at room temperature and exhibited reversible synthesis reactions. This result provided confidence that, through optimized molecular design, stable handling of antiaromatic compounds is achievable.

The antiaromatic isophlorin synthesized in Chapter 2 possessed four nitrogen atoms capable of coordinating with metal ions, suggesting potential modulation of physical properties through various metal introductions. Therefore, in Chapter 3, the author aimed to synthesize antiaromatic isophlorin metal complexes, initially investigating Sn(IV) complexes adopting a six-coordinate structure. The obtained isophlorin Sn(IV) complex exhibited improved planarity and stronger antiaromaticity compared to the structure before metal introduction. Other isophlorin metal complexes were also investigated, suggesting that in the Pd(II) complex, the emergence of a conjugated pathway involving the Pd atom might weaken the antiaromaticity.

Regarding metal complexes of antiaromatic isophlorin, in Chapter 4, the author aimed to synthesize sandwich-type isophlorin complexes using lanthanide atoms. It is known that antiaromatic compounds exhibit aromaticity when they are stacked. The sandwich-type isophlorin complex can be interpreted as a structure where two antiaromatic isophlorin molecules are stacked, making it an optimal molecular structure for elucidating this phenomenon. First, the reduction behavior of the precursor sandwich-type porphyrin complex was investigated. An electrochemical four-electron reduction wave was observed, providing insights leading to the synthesis of the sandwich-type isophlorin complex.

Chapter 5 focused on the substituent effect on antiaromaticity. Quantum chemical calculations were performed on heteroatom-substituted antiaromatic isophlorin analogues. It was found that the frontier orbitals of isophlorin analogues differ significantly based on the type and position of substituents, allowing for the modulation of antiaromaticity strength.

These results indicate that antiaromatic compounds gain stability through delocalization of their orbitals upon substituent introduction or metal complexation. Conversely, when substituents capable of extending π -conjugation are introduced, the compound's orbitals significantly expand to include the substituent, reducing the strength of antiaromaticity. This insight opens synthetic pathways not only for antiaromatic isophlorins but also for other derivatives of antiaromatic compounds. Antiaromatic compounds exhibit unique electronic structures, such as narrow HOMO–LUMO gaps, making them promising candidates for applications in electronic devices. This work is expected to contribute to the development of numerous antiaromatic compounds, applied research utilizing their unique electronic structures, and ultimately the creation of novel functional molecules and materials.

List of Publications

Foundational Papers

1. Chapter 2.

“20 π Antiaromatic Isophlorins without Metallation or Core Modification”

Haruna Sugimura, Kana Nakajima, Ken-ichi Yamashita, and Takuji Ogawa

Eur. J. Org. Chem. **2022**, e202200747. (DOI: 10.1002/ejoc.202200747)

*Selected as a very important paper and a front cover.



2. Chapter 3.

“Synthesis and Characterization of an Air-Stable Tin(IV) β -Tetracyanoisophlorin Complex: Enhanced Antiaromaticity through Metal Complexation”

Haruna Sugimura, Kana Nakajima, and Ken-ichi Yamashita

Asian J. Org. Chem. **2025**, 14, e202400550. (DOI: 10.1002/ajoc.202400550)

3. Chapter 4.

“Lanthanum β -Tetracyanoporphyrin Double-Decker Complexes: Four-Electron Reduction and Slow Ligand Rotation”

Haruna Sugimura, Wataru Imanaka, and Ken-ichi Yamashita

Chem. Eur. J., just accepted.

4. Chapter 5.

“Tuning Antiaromaticity through *meso*-Substituent Orientation in Core-Modified Isophlorins”

Maika Isoda,[#] **Haruna Sugimura**,[#] Kensuke Honda, and Ken-ichi Yamashita [#]Equal contribution.

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