

The Preparation and Catalytic Activity of
Iron Phthalocyanine μ -oxo Dimers

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BY

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Dr. Victor N. Nemykin

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Dedication

I would first like to dedicate this thesis to my husband. He was there every step of the way and I could not have done it without him.

Secondly I would like to dedicate this thesis to my family. They were there when I was growing up to support my love for science and gave me every opportunity to pursue my passion.

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Chapter 1 Introduction

1.1 History and Importance of Phthalocyanines

It is commonly accepted that in 1907 the first metal-free phthalocyanine was synthesized by accident and reported as an unknown solid dark blue side product during the preparation of *o*-cyanobenzamide by Braun and Tcherniac.¹ Twenty years later the first metallophthalocyanines were reported. The first was a copper phthalocyanine, reported by de Diesbach and von der Weid, as an insoluble dark blue product discovered during a reflux reaction with copper(I) cyanide and 1,2-dibromobenzene in pyridine.² This process is now known as the Rosenmund-von Braun reaction.² The second was an iron phthalocyanine, discovered in a damaged reactor and reported as a dark blue-green solid by scientists at Imperial Chemical Industries during a high-temperature preparation of phthalimide from phthalic anhydride.³

In the 1930s, Linstead and coworkers conducted an extensive study to accurately characterize the structures of unsubstituted metal-free and metallophthalocyanines, with the X-ray diffraction analysis of the compounds completed by Robertson.⁴ The structure of unsubstituted metal-free and metallophthalocyanines is presented in figure 1.1.

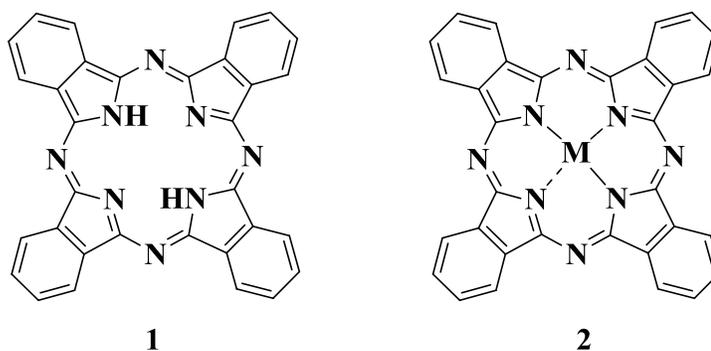


Figure 1.1. Structure of Unsubstituted Metal-free Phthalocyanine (1) and Unsubstituted Metallophthalocyanine (2).

Since their discovery and characterization, phthalocyanines have been widely used as blue-green dyes and pigments, catalysts for sulfur-removing reactions for the processing of oil, and as photo conducting agents in copying machines, due to their intense color and unique properties.^{5a} For these uses and many more, over 50,000 tons of phthalocyanines are produced each year.^{5a}

The use of phthalocyanines in photodynamic therapy has been extensively studied.⁶ Photodynamic therapy utilizes the fact that certain compounds can accumulate in one area and cause only localized damage to surrounding cells upon excitation from a specific light source. Phthalocyanines are attractive for use in photodynamic therapy due to many of their unique properties. Phthalocyanines are nontoxic, have tumor localization capabilities, absorb light at the appropriate wavelengths for deep tissue penetration, have high photodynamic efficiency, and display appropriate excited state properties.^{6,7} To date, sulfonated Al^{3+} and Zn^{2+} metallophthalocyanines have been employed as photodynamic agents for the targeting and treatment of malignant cells.⁶

Another research area for phthalocyanines is their incorporation into molecular

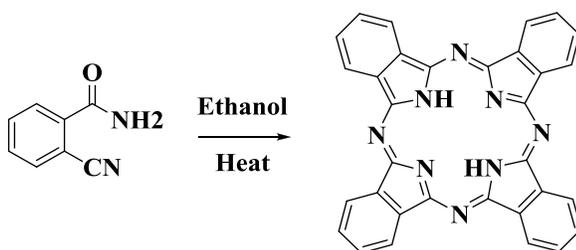
electronic devices where they exhibit many advantageous properties. Switching times of less than 10^{-12} seconds and continued operation up to 300°C have been displayed.

Through the use of phthalocyanine molecules, micrometer scale elements can be produced without super clean facilities, and are compatible with semiconducting systems.⁸ These properties and many more make phthalocyanines useful for dynamic memory elements and for use in multisignal processing.⁸

Phthalocyanines have been widely investigated in oxidation reactions because of their similar structure to porphyrins, which have been shown to be effective catalysts for oxidations in some biological systems.^{5b} Lyons and Ellis recently showed that $\text{Cr}(\text{Pc})\text{N}_3$, $\text{Mn}(\text{Pc})\text{N}_3$ and $\text{Fe}(\text{FPc})\text{N}_3$ catalyzed the oxidation of isobutene to *tert*-butyl alcohol with 91%, 88% and 82% yields, respectively.^{5b,c} Cobalt(II) phthalocyanine is used as a catalyst during mercaptan oxidation which is used in oil refineries and natural gas processing facilities to oxidize thiol impurities to disulfides to aid in removal of sulfur.^{5b} Lastly, iron(II)TSPc has been used as a catalyst to break down 2,4,6-trichlorophenol, a harmful pollutant produced by paper mills, into chloromaleic, chlorofumaric, maleic and fumaric acids.^{5b} These acids are easier to remove from waste water than 2,4,6-trichlorophenol.

1.2 General Synthesis of Unsubstituted Phthalocyanines

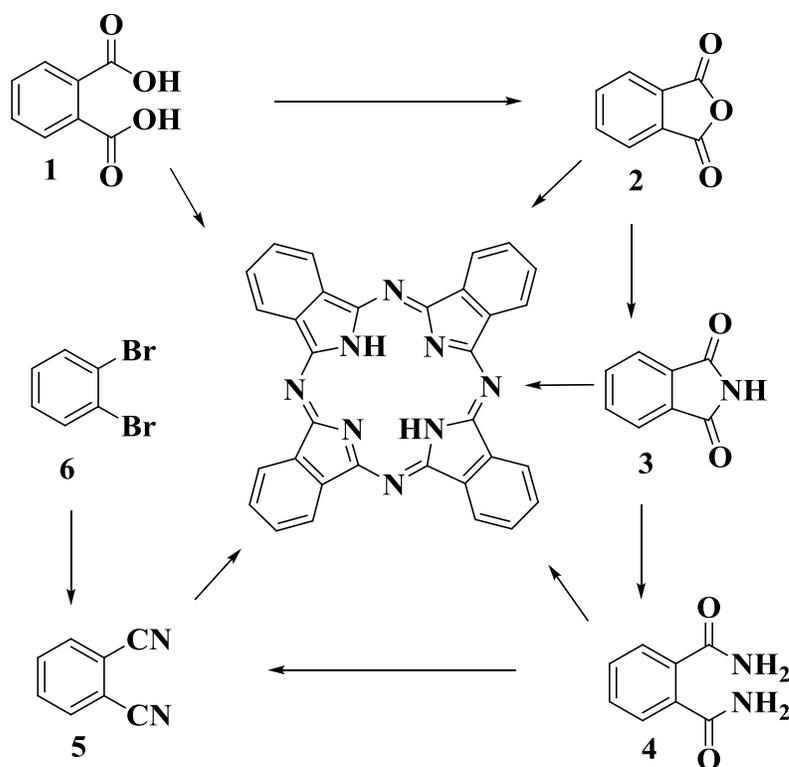
The first phthalocyanine was synthesized as depicted in scheme 1.1.



Scheme 1.1. First Synthesis of an Unsubstituted Metal-free Phthalocyanine

It was prepared by refluxing 2-cyanobenzamide in ethanol.¹ An unsubstituted metal-free phthalocyanine was recovered, but the yield from this reaction was very low.¹ The 2-cyanobenzamide precursor to phthalocyanine production has now been replaced with a phthalonitrile precursor which offers better yields.

Two pathways to produce a phthalocyanine through a phthalonitrile intermediate are illustrated in scheme 1.2



Scheme 1.2. Synthetic Pathways to an Unsubstituted Metal-free Phthalocyanine

The first procedure starts with a phthalic acid **1** which undergoes multiple reactions producing intermediates (phthalic anhydride **2**, phthalimide **3**, and phthalamide **4**) to be finally converted into a phthalonitrile **5**. The second procedure is known as the Rosenmund-von Braun reaction and starts with a 1,2-dihalide substituted benzene **6** and reacts with copper cyanide to produce the desired phthalonitrile **5**.

The phthalonitrile is reacted under basic conditions in a suitable high boiling solvent such as N,N-dimethylethanolamine to form the corresponding phthalocyanine.⁹ If the starting material is an unsubstituted ortho-dicarboxylic acid **1** or 1,2-dihalide substituted benzene **6**, the product will be an unsubstituted phthalocyanine. The unsubstituted phthalocyanine is easy to form from the phthalonitrile precursor, but once formed it has a low solubility in organic solvents in the order of $10^{-6} - 10^{-7}$ M or less. This prompted researchers to start with substituted precursors or to add substituents onto the benzene rings of the phthalocyanine to increase the solubility.

1.3 Substituted Phthalocyanines

The addition of substituents to positions, as numbered in figure 1.2, greatly increases the solubility of the phthalocyanine.

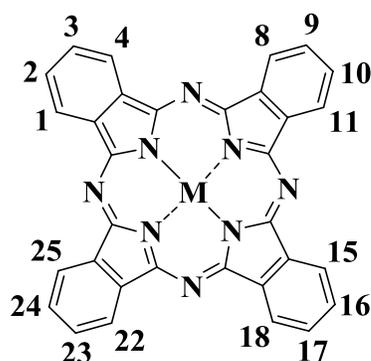
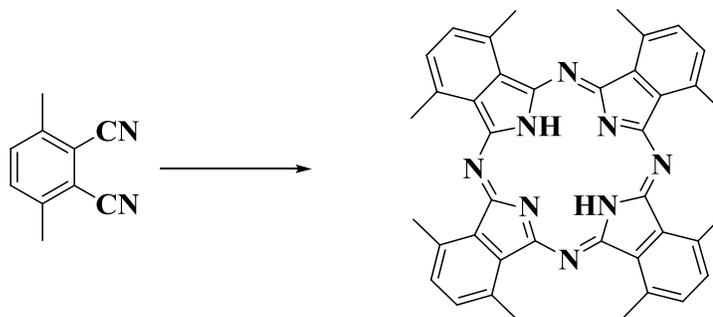


Figure 1.2. IUPAC Nomenclature for the Phthalocyanine Core

There are two ways to add substituents to a phthalocyanine core. The first involves modifying the existing phthalocyanine using electrophilic aromatic substitution reactions.^{10,11} The second involves the use of a substituted phthalonitrile precursor in the tetramerization reaction to produce a substituted phthalocyanine.¹⁰ For example, if 3,6-dimethylphthalonitrile is refluxed in N,N-dimethylethanolamine, the resulting product is 1,4,8,11,15,18,22,25-octamethylphthalocyanine which is shown in scheme 1.3.



Scheme 1.3. Preparation of Octasubstituted Phthalocyanines

This is not the case for tetrasubstituted phthalocyanines. If 3-methylphthalonitrile is refluxed in N,N-dimethylethanolamine, a single product is not observed, but a

combination of four positional isomers as illustrated in figure 1.3. In theory these isomers can be separated, but it would only be possible by using a specially designed HPLC column.¹² Since the differences in properties of these positional isomers is negligible, such mixtures are always used without further purification.

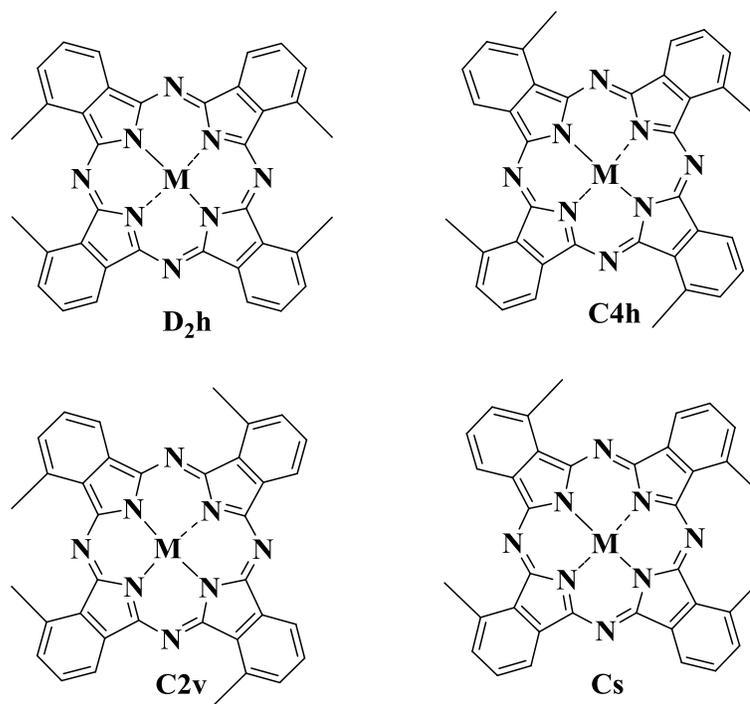


Figure 1.3. Four Possible Isomers of Tetrasubstituted Metallothalocyanines

When presenting the tetra-*tert*-butylsubstituted phthalocyanines in this thesis work it should be noted that the phthalocyanine is not a pure isomer, but a combination of the four.

1.4 Single-Atom Bridged Iron Phthalocyanine Dimers

Iron phthalocyanine μ -oxo dimer **1** is known for its stability and the ease at which it is formed. For example, it can be formed by dissolving iron phthalocyanine in concentrated sulfuric acid, then bubbling oxygen through the solution for twenty minutes. The solution is then poured into cold water and the iron phthalocyanine μ -oxo dimer in its linear form ($\text{Fe-O-Fe} \sim 180^\circ$) is recovered as a precipitate.¹³ In order to form the bent isomer ($\text{Fe-O-Fe} < 180^\circ$), iron phthalocyanine is dissolved in DMF, THF, or dioxane with stirring and left open to the atmosphere. The bent iron phthalocyanine μ -oxo dimer can then be isolated from the reaction mixture.¹⁴

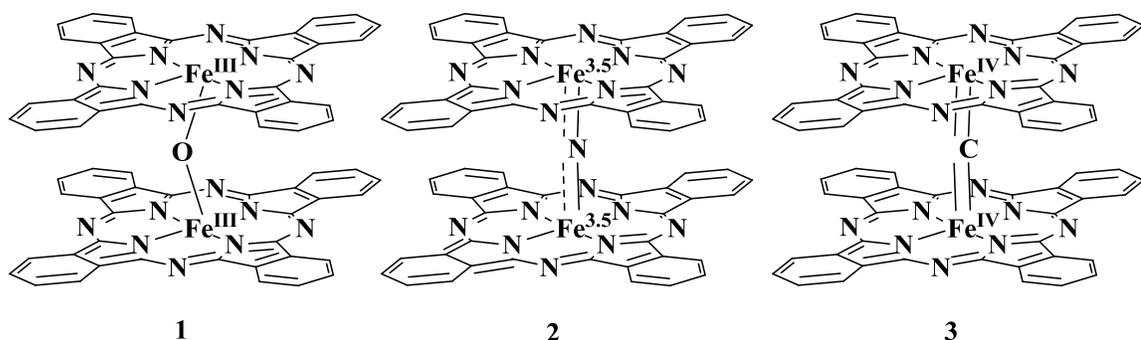


Figure 1.4. Three Different Iron Phthalocyanine Dimers

Two other iron phthalocyanine dimers have been reported, μ -nitrido **2** and μ -carbido **3**. The μ -nitrido iron phthalocyanine dimer is obtained by heating either iron phthalocyanine or iron phthalocyanine μ -oxo dimer with sodium azide in chloronaphthalene.¹⁵ The μ -carbido iron phthalocyanine dimer is prepared by dissolving iron phthalocyanine and carbon tetraiodide in chloronaphthalene with a reducing agent such as sodium dithionite and then heating at $140\text{-}150^\circ\text{C}$ for 30 minutes.¹⁶

The three iron dimers depicted above have similar structures but very different properties. The Mössbauer spectrum for iron phthalocyanine μ -oxo dimer **1** has a single signal with an isomer shift and quadruple splitting values of 0.36 and 0.44 mm s⁻¹, respectively at 77K.^{17,18} These data, along with magnetic susceptibility, confirm that the iron phthalocyanine μ -oxo dimer **1** contains two antiferromagnetically coupled high-spin (5/2, 5/2) iron(III) centers. The Mössbauer spectrum of iron phthalocyanine μ -nitrido dimer **2** also has a single signal, but with an isomer shift and quadruple splitting values of 0.06 and 1.76 mm s⁻¹, respectively at 77K.^{17,18} The spectrum indicates that the iron phthalocyanine μ -nitrido dimer **2** on the Mössbauer time scale (10⁻⁸ s) contains two delocalized iron centers, which average out to two irons with a charge of + 3.5 (class III mixed valence compound in the Robin-Day classification). The Mössbauer spectrum of the iron phthalocyanine μ -carbido dimer **3** contains a single signal with an isomer shift and quadruple splitting values of -0.16 and 2.69 mm s⁻¹, respectively at 77K.^{17,18} This clearly indicated that the iron phthalocyanine μ -carbido dimer **3** contains two iron(IV) centers.^{17,18}

Recently iron phthalocyanine μ -nitrido dimer **2** was reported to be catalytically active towards the oxidation of thiols to disulfides, methane to formic acid, methanol to formic acid and hydroquinone to quinone.^{19a,b} Also, it is well known that monomeric iron phthalocyanines are catalytically active towards the oxidation of phenols and hydrocarbons.²⁰ With this knowledge, research was conducted to test the catalytic ability of the iron phthalocyanine μ -oxo dimer **1**.

This thesis will provide evidence for the catalytic ability of iron phthalocyanine

μ -oxo dimer **1** towards oxidation reactions, even though iron μ -oxo dimers have traditionally been considered inactive. Secondly, it will present a wide variety of substrates that can be oxidized by iron phthalocyanine μ -oxo dimer **1** with several oxidants. It will also present new alternative oxidants to the widely used polymeric iodosylbenzene and organic peroxides.

Chapter 2

Comparison Study of Metalled Tetraphenylporphyrins Versus Iron(III) Phthalocyanine μ -Oxo Dimer as Catalysts for the Oxidation of Alcohols Using Organic Iodine(V) Compounds as Terminal Oxidants

2.1 Introduction

The catalytical properties of transition metal porphyrins with respect to the oxidation of substrates have been well documented.²¹ Recently, supported monomeric and dimeric iron phthalocyanine catalysts,²² and ruthenium and cobalt meso-tetraphenylporphyrin chloride²³ have been shown to be catalytically active towards alcohol oxidations. To add to the knowledge of metal porphyrins and phthalocyanines as catalysts for the oxidation of alcohols, new hypervalent iodine compounds were prepared and used as oxidants.

Hypervalent iodine compounds are used extensively in organic synthesis as highly selective and environmentally friendly oxidizing reagents.²⁴ Among these reagents, iodosylbenzene, (PhIO)_n, is particularly important as an oxygen transfer agent. It has found widespread application in catalytic oxygenation reactions after the discovery of its supreme efficiency as a source of oxygen atoms for oxidations catalyzed by cytochrome P-450 and by discrete transition metal complexes.^{25,26} Despite its value as an oxidant, practical applications of iodosylbenzene are hindered by its low solubility in organic solvents,²⁶ as well as low thermal stability and explosive properties upon moderate heating.²⁷

In this chapter, the preliminary results on the use of stable and soluble pseudocyclic hypervalent iodine(V) reagents **1–3** (Fig. 2.1) as terminal oxidants in the biomimetic oxidation of alcohols catalyzed by the iron(III) phthalocyanine complex **4** or metal porphyrin complexes **5** and **6** (Fig. 2.2) will be reported. Complex **4** was prepared using a direct high-temperature reaction between 4-tert-butylphthalonitrile and iron(II) acetate as described previously,²⁸ while Co(II) tetraphenylporphyrin **5** and Ru(II)-carbonyl tetraphenylporphyrin **6** were used from commercial sources.

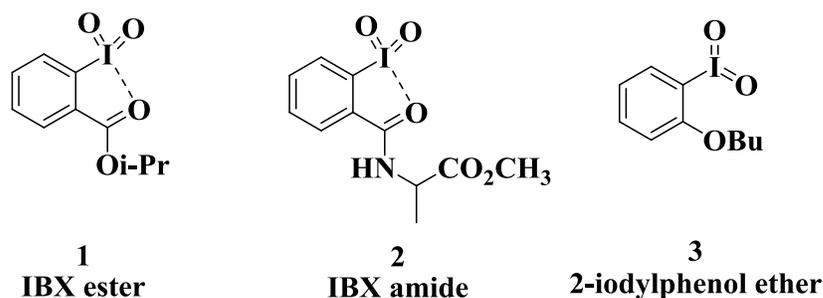


Figure 2.1. Hypervalent Iodine(V) Oxidants

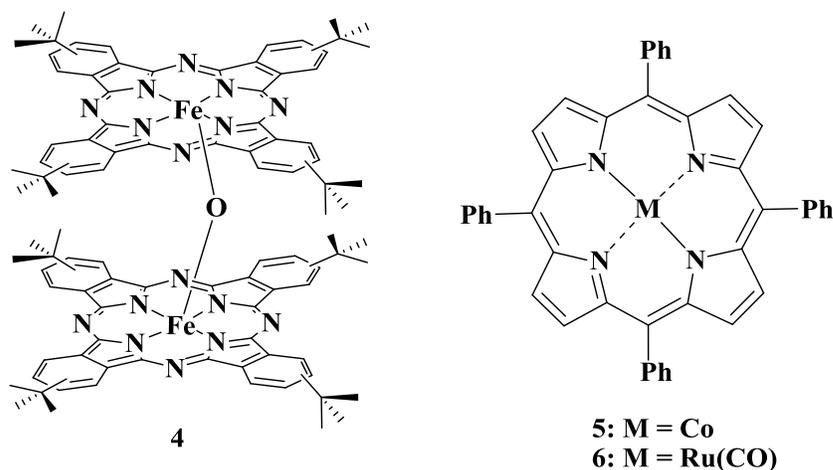


Figure 2.2. Iron(III) Phthalocyanine μ -oxo dimer (**4**) and Metal Porphyrin Complexes (**5** and **6**)

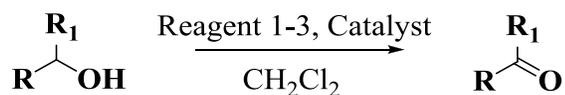
2.2 Experimental Setup

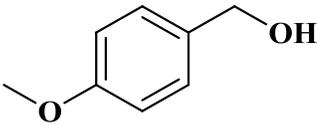
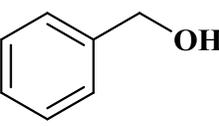
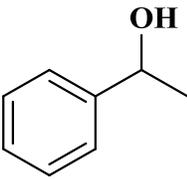
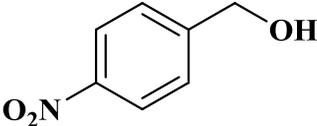
Isopropyl ester of 2-iodylbenzoic acid **1** was prepared by the hypochlorite oxidation of the readily available isopropyl ester of 2-iodobenzoic acid and was isolated in the form of a stable, white, microcrystalline solid.^{29a} Compound **1** is also commercially available from several chemical companies.^{29b} 2-Iodylbenzamide **2**^{30a} and 2-iodylphenol ether **3**^{30b} were prepared by oxidation of the respective iodides using dimethyldioxirane. Both reagents are isolated as stable and non-explosive microcrystalline products. The previously reported X-ray studies of compounds **1–3** revealed the presence of strong intramolecular I···O interactions, which partially replace the intermolecular I···O secondary bonds disrupting the polymeric structure typical of other ArIO₂.^{29,30} Due to this structural feature, compounds **1–3** have excellent solubility in non-polar organic solvents and can be used as efficient and convenient oxidizing reagents.^{29–31}

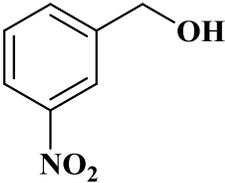
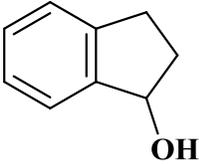
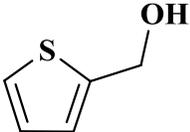
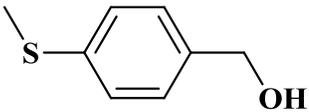
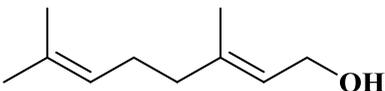
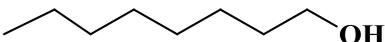
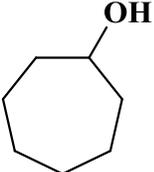
To a vigorously stirred solution of reagents **1–3** (0.08 mmol) and catalysts **4–6** (0.011 mmol) in dry dichloromethane (3 ml), the appropriate alcohol (0.11 mmol) was added. The resulting solution was stirred at room temperature for the indicated time (Table 2.1). A portion of the crude reaction mixture (0.1 ml) was passed through 1 cm of silica gel suspended in a Pasteur pipet and washed with the mixture of hexane and ethyl acetate 3:2 (1 ml). The resulting solution was analyzed by GC–MS to determine the conversion of alcohol **7** to the respective carbonyl compound **8**.

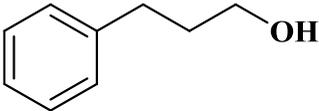
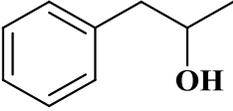
2.3 Results and Discussion

Table 2.1. Catalytic Oxidation of Alcohols (**7**) to Carbonyl Compounds (**8**) Using Hypervalent Iodine Reagents.^a



Entry	Reagent	Catalyst	Substrate (7)	Conversion (preparative yield) (%)	Time (h)
1a	1	4		100 (95)	1
1b	1	5		15	22
1c	1	6		100	1.5
1d	2	4		31	2.5
1e	3	4		11	2
1f	PhIO ^b	4		68	3
1g	1	none		0	24
2a	1	4		100	1.5
2b	1	5		0	48
2c	1	6		94	3
2d	3	4		53	3
2e	1	none		55	168
3a	1	4		100 (91)	2
3b	1	6		100	2.5
3c	3	4		54	3
4a	1	4		100	0.5
4b	1	5		3	24
4c	1	6		100	1
4d	3	4		100	0.5
4e	PhIO ^b	4		96	1.5

5	1	4		100	3
6a	1	4		31	5
6b	1	4 ^c		70 ^c	4
6c	1	6		100	2.5
6d	3	4		31	5.6
7	1	4		24	3
8	1	4		20 ^d	3
9a	1	4		100	1
9b	3	4		100	2.5
9c	PhIO ^b	4		100	1
10a	1	4		22	7
10b	1	4 ^c		25 ^c	3
11	1	4		11	8

12	1	4		10	4.5
13	1	4		6	3.5

^a All oxidations were carried out at room temperature in dry dichloromethane with 0.7 equiv. of reagents **1**, **2**, or **3** and 0.1 equiv. of catalyst. Catalyst was removed by flash chromatography and the obtained solution was analyzed by GC–MS.

^b 1.5 equiv. of PhIO was used.

^c Oxidations were carried out under reflux conditions.

^d No products of oxidation on sulfur were observed.

The catalytic oxidation of alcohols to carbonyl compounds was investigated using oxidants **1–3** and complexes **4–6**. The use of iodosylbenzene in the catalytic oxidation of alcohols in the presence of various transition metal complexes has previously been documented in the literature.³²

According to the GC–MS and NMR data, carbonyl compounds **8** and the appropriate iodides resulting from the reduction of reagents **1–3** were the only products formed under these reaction conditions. Dichloromethane was found to be the best solvent, as the conversion was found to be much lower when the oxidation was performed in toluene or acetonitrile.

Using benzylic alcohols as model substrates, we have found that IBX-ester **1** is the most efficient stoichiometric oxidant in the catalytic oxidation reactions. Indeed, the oxidation of 4-methoxybenzyl alcohol using oxidant **1** at room temperature in the presence of an Fe(III) phthalocyanine complex **4** (10 mol %) affords the respective aldehyde in a 100% conversion (95% isolated yield after chromatography) after one hour

of stirring at room temperature (Table 2.1, entry 1a). The conversion is much lower when reagents **2** and **3** are employed for the oxidation of benzylic alcohols under similar conditions using the same catalyst **4** (entries 1d, 1e, 2d, 3c, 4d, and 6d). Iron(III) phthalocyanine complex **4** and ruthenium(II)-carbonyl tetraphenylporphyrin **6** are the most efficient catalysts in these oxidations. The oxidations in the presence of Ru(II) complex **6** (entries 1c, 2c, 3b, 4c, and 6c) proceed only slightly slower compared to the Fe(III) complex **4** (entries 1a, 2a, 3a, 4a, 5, and 6a,b), while the Co(II) tetraphenylporphyrin **5** did not show any significant catalytic effect (entries 1b, 2b, and 4b). The availability and low cost of the iron(III) complex **4**, as compared to those of the ruthenium porphyrin **6**, clearly make it a potentially useful reagent for biomimetic catalytic transformations.

The oxidation of alcohols with reagent **1**, in the absence of catalyst, proceeds extremely slowly and shows measurable conversion to the aldehyde only after four to seven days of stirring at room temperature (entries 1g and 2e).³³ The sulfur-containing benzylic alcohols (entries 7 and 8) show significantly lower reactivity in the catalytic oxidations, and the oxidation of organic sulfur to sulfoxide or sulfone is not observed under these conditions. The allylic alcohol demonstrates about the same reactivity in the catalytic oxidations (entries 9a,b), while the aliphatic substrates are much less reactive (entries 10–13).

IBX ester **1** and iodosylbenzene show similar reactivity in the oxidation of the same substrates in the presence of the Fe(III) phthalocyanine complex **4** as the catalyst (compare entries 1a and 1f, 4a and 4e, 9a and 9c). Both iodosylbenzene and reagent **1** are

commercially available or can be conveniently prepared from common precursors. However, in contrast to the insoluble, thermally unstable, and potentially explosive iodosylbenzene,^{26,27} reagent **1** is soluble in organic solvents, can be stored for extended periods at room temperature, and is not explosive. The results of the comparative studies (Table 2.1) confirms that IBX ester **1** can be effectively used as a stoichiometric oxidant in biomimetic oxidations catalyzed by metal porphyrin or phthalocyanine complexes.

Chapter 3

Comparison Study of Metalled Tetraphenylporphyrin Versus Iron(III) Phthalocyanine μ -Oxo Dimer as Catalysts for the Oxygenation of Hydrocarbons using Iodosylbenzene Sulfate and 2-Iodylbenzoic Acid Ester as Safe and Convenient Alternatives to Iodosylbenzene

3.1 Introduction

Metal phthalocyanines and porphyrins have been shown to be catalytically active towards C-H bond activated oxidations.³⁴ To build upon this information, tests were conducted to assess the catalytic ability of two metal porphyrins and one metal phthalocyanine with new hypervalent iodine compounds as oxidants in the oxidation of hydrocarbons.

Hypervalent iodine compounds are versatile, selective oxidants that have the added advantage of being biodegradable and low in toxicity.^{35,36} Among these reagents, iodosylbenzene, (PhIO)_n, is particularly important as an efficient oxygen transfer agent that has found widespread application in various oxygenation reactions.³⁶ In 1979 Groves and co-workers reported that iodosylbenzene is the most efficient source of oxygen for the oxygenation of hydrocarbons in the presence of iron (III) porphyrin complexes,^{37a} and since then (PhIO)_n has been widely used as a terminal oxidant in the reactions mimicking natural oxidations performed by the heme-containing cytochrome P-450 class of enzymes.³⁷ Despite its usefulness as an oxidant, practical applications of iodosylbenzene are hindered by its low solubility,³⁶ low thermal stability, and explosive properties upon

moderate heating.³⁸

In this chapter, results on the use of the new and convenient hypervalent iodine reagents **1** and **2** (Figure 3.1) as terminal oxidants in the biomimetic oxidation of anthracene to anthraquinone catalyzed by Fe (III) phthalocyanine complex **3** (Figure 3.2), Co(II) tetraphenylporphyrin **4** or Ru(II) tetraphenylporphyrin **5** will be reported.

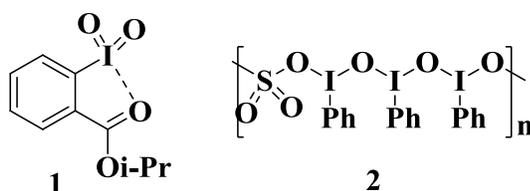


Figure 3.1. Hypervalent Iodine Oxidants: Isopropyl 2-iodylbenzoate (**1**) and Oligomeric Iodosylbenzene Sulfate (**2**)

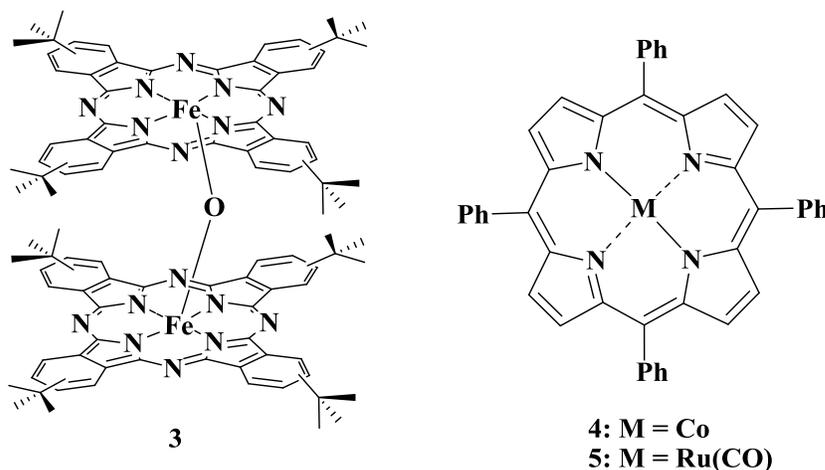


Figure 3.2. Iron(III) Phthalocyanine μ -oxo dimer (**3**) and Metal Porphyrin Complexes (**4** and **5**)

3.2 Experimental Setup

The oligomeric iodosylbenzene sulfate $[(\text{PhIO})_3 \cdot \text{SO}_3]_n$ **2** was prepared by simple treatment of commercially available (diacetoxyiodo)benzene with aqueous hydrogen

sulfate and isolated as a thermally stable, yellow crystalline solid.³⁹ The isopropyl ester of 2-iodylbenzoic acid (IBX-ester) **1** was prepared by the hypochlorite oxidation of the readily available isopropyl ester of 2-iodobenzoic acid and isolated in the form of a stable, white, microcrystalline, solid.^{40 a,b} Reagent **1** is also commercially available from several chemical companies.^{40c} Complex **3** was prepared using the direct high-temperature reaction between 4-tert-butylphthalonitrile and iron(II) acetate as described previously,⁴¹ while Co(II) tetraphenylporphyrin **4** and Ru(II) carbonyl tetraphenylporphyrin **5** were obtained from commercial sources. The heterogenized phthalocyanine catalysts similar to complex **3** were previously reported in the C-H activation reactions using H₂O₂ or organic peroxides as source of oxygen.⁴² Recently, we have reported the use of complexes **3–5** in the catalytic oxidations of alcohols.⁴³

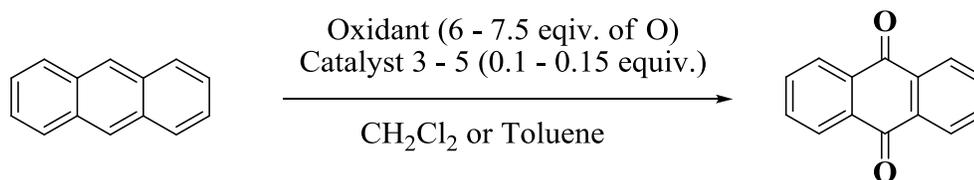
All reactions were performed under a dry nitrogen atmosphere with flame-dried glassware. All commercial reagents were ACS reagent grade and used without further purification. Dichloromethane was distilled from CaH₂ and stored over molecular sieves (4 Å). Co(II) tetraphenylporphyrin **4** and Ru(II) carbonyl tetraphenylporphyrin **5** were obtained from commercial sources. Iodosylbenzene sulfate **2** and isopropyl ester of 2-iodylbenzoic acid (IBX-ester) **1** were prepared according to previously reported procedures.^{39,40a} Iodosylbenzene was prepared by a known method involving the alkaline hydrolysis of (diacetoxyiodo)benzene.^{36a} GC-MS analysis was carried out with an HP 5890 A Gas Chromatograph using a 5970 Series mass selective detector.

The typical procedure used for catalytic oxidation of anthracene, a solution of anthracene (6; 0.10–0.15 mmol) in toluene or dichloromethane (3–5 mL) was mixed with

the appropriate catalyst (0.010–0.015 mmol) and the hypervalent iodine oxidant (6–7.5 equiv. of O), with stirring, at the indicated temperature (see Table 3.1). Samples of the reaction mixture (50 mL) were collected every 30 minutes, filtered through 2–3 cm of silica gel suspended in a Pasteur pipet, washed with a mixture of ethyl acetate and hexane (2:3 v:v), and analyzed using GC-MS.

The procedure used for the catalytic oxidation of 2-*tert*-butylanthracene follows. A solution of 2-*tert*-butylanthracene (8; 16 mg, 0.068 mmol) in toluene (2.5 mL) was mixed with Fe(III) phthalocyanine complex 3 (15 mg, 0.0094 mmol) and reagent 2 (110 mg, 0.15 mmol) and was stirred 24 hours at room temperature. The solvent was removed and the residue was separated by column chromatography on silica gel (ethyl acetate/hexane, 1:20) to give 2-*tert*-butylanthraquinone 9 as yellow needles; yield:13 mg (72%); mp 101–102.5°C (Lit.⁴⁵ mp 103–104°C).

3.3 Results and Discussion



Scheme 3.1. Catalytic Oxidation of Anthracene (**6**) to Anthraquinone (**7**)

Table 3.1. Catalytic Oxidations of Anthracene (**6**) to Anthraquinone (**7**) Using Hypervalent Iodine Reagents.

Entry	Reagent		T (°C)	Catalyst		Solvent	Conversion (%)	Time (h)
		Mol equiv			Mol. %			
1	1	3	rt	none	0	toluene	0	24
2	1	3	40	none	0	CH ₂ Cl ₂	0	24
3	1	3	110	none	0	toluene	14	3.5
4	1	3	110	none	0	toluene	86	24
5	1	3	rt	3	15	toluene	0	24
6	1	3	110	3	15	toluene	100	2.5
7	1	3	110	4	15	toluene	14	3.5
8	1	3	110	5	15	toluene	0	21
9	1	3	40	5	15	CH ₂ Cl ₂	100	0.5
10	1	3	rt	5	10	CH ₂ Cl ₂	100	3.5
11	2	2.5	rt	none	0	toluene	0	24
12	2	2.5	rt	3	10	toluene	100	2
13	2	2.5	rt	4	10	CH ₂ Cl ₂	100	2
14	2	2.5	rt	5	10	CH ₂ Cl ₂	100	1
15	PhIO	7.5	rt	none	0	toluene	0	24
16	PhIO	7.5	rt	3	10	toluene	100	5
17	PhIO	7.5	rt	5	15	CH ₂ Cl ₂	7	3
18	PhIO	7.5	rt	5	15	CH ₂ Cl ₂	100	24
19	PhIO	7.5	rt	4	15	CH ₂ Cl ₂	26	2

The catalytic oxidation of anthracene **6** to anthraquinone **7** has been investigated using oxidants **1**, **2**, and complexes **3–5** (Scheme 3.1) in comparison with iodosylbenzene

as the common oxygenating reagent. The use of iodosylbenzene in this reaction, in the presence of transition metal complexes, was previously reported in the literature.⁴⁴

According to the GC-MS and NMR data, anthraquinone **7** and the appropriate iodides resulting from the reduction of hypervalent iodine reagents were the only products formed under these reaction conditions. Dichloromethane was found to be the best solvent for the oxidations in the presence of metal porphyrins **4** and **5**. Toluene was used for the reactions catalyzed by Fe(III) phthalocyanine **3** due to the instability of complex **3** in dichloromethane solutions.

It was found that the oxidation of anthracene with hypervalent iodine reagents **1** and **2** in the absence of catalysts at room temperature in toluene or at 40°C in dichloromethane proceeds extremely slowly and does not show any measurable conversion to anthraquinone after 24 hours (entries 1, 2, and 11). Reagent **1**, however, slowly oxidizes anthracene in toluene under reflux conditions (110°C) with a 14% conversion after 3.5 hours and 86% conversion after 24 hours (entries 3 and 4). The addition of 0.15 mol equiv. of Fe(III) phthalocyanine **3** leads to a significant increase in the reaction rate with a 100% conversion being reached in 2.5 hours at 110°C (entry 6). The graphical representation of the conversion in this reaction versus time is shown in Figure 3.3. Lowering the reaction temperature leads to a slower conversion rate in the reaction in the presence of iron (III) phthalocyanine **3** (entry 5).

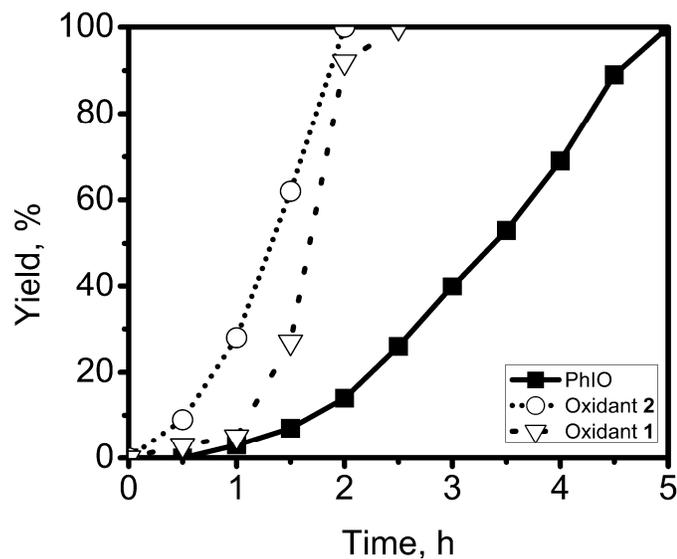


Figure 3.3. Conversion in the Catalytic Oxidation of Anthracene (**6**) to Anthraquinone (**7**) using Oxidant (**1**) at 110°C, Oxidant (**2**) at Room Temperature and Iodosylbenzene at Room Temperature in the presence of the Fe(III) Phthalocyanine Complex (**3**)

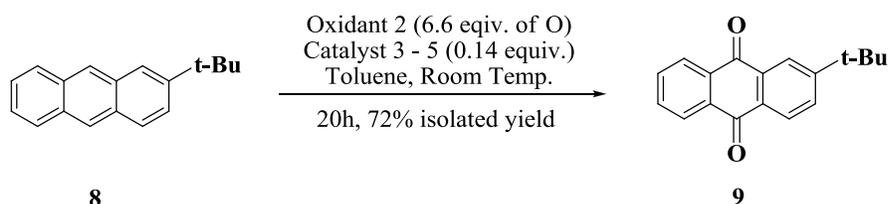
The use of Co(II) tetraphenylporphyrin **4** and Ru(II) carbonyl tetraphenylporphyrin **5** as catalysts in this oxidation, under the same reaction conditions, (110°C, toluene) leads to a significantly lower conversion (14%, entry 7 and 0%, entry 8, respectively), which is even lower than the conversion in the absence of a catalyst (entries 3 and 4). This result is probably explained by the low thermal stability of the intermediate high valent oxo-metal complexes generated from the initial interaction of metal porphyrins **4** and **5** and the oxidant. Lowering the reaction temperature leads to a fast and efficient oxidation in the presence of catalyst **5** (entry 9: 100% conversion in 0.5 hours at 40°C; entry 10: 100% conversion in 3.5 hours at room temperature). It should be emphasized that IBX-ester **1** is more reactive in this reaction than the commonly used iodosylbenzene, which shows only 7% conversion after 3 hours and 100% conversion

only after a 24 hour period in the presence of Ru(II) porphyrin **5** (entries 17 and 18, respectively). The Co(II) porphyrin **4** shows slightly lower catalytic activity in these oxidations (entries 13 and 19).

In contrast to IBX-ester **1**, the oligomeric iodosylbenzene sulfate **2** shows high reactivity in catalytic oxidations at room temperature in the presence of any of the catalysts **3–5** (10 mol%), while the reaction in the absence of catalysts at room temperature does not occur (entry 11). The best catalytic effect is observed in the presence of Ru(II) porphyrin **5** (entry 14; 100% conversion in 1 hour). The reactivity of oxidant **2**, in the presence of catalysts **3** and **4**, is slightly lower (entries 12 and 13; 100% conversion in 2 h). The graphical representation of the conversion in the oxidations using reagents **1** and **2** catalyzed by the iron(III) phthalocyanine complex **3** versus time is shown in Figure 3.3 in comparison with the analogous oxidation using iodosylbenzene.

The data presented in Table 3.1 and Figure 3.3 clearly indicates that the oligomeric iodosylbenzene sulfate **2** is the best oxidant, significantly more reactive than the commonly used iodosylbenzene. The slower reaction with iodosylbenzene can partially be explained by its polymeric structure, (PhIO)_n, requiring initial depolymerization, while the structure of sulfate **2** consists of smaller trimeric units of PhIO. The presence of the initial period of activation in the reaction of (PhIO)_n is clearly observed on its reactivity curve (Figure 3.3). The reaction of IBX-ester **1** in the presence of the iron(III) phthalocyanine complex **3** requires heating to 110°C. This need for higher temperature can be explained by the low solubility of reagent **1** in toluene, which is the preferable solvent for the reactions involving catalyst **3**. The reactivity of both oxidants **1**

and **2** is similar when a more stable Ru(II) complex **5** is used in the dichloromethane solution (entries 9, 10 and 14). Overall, ruthenium(II) complex **5** shows the highest catalytic activity, however, the availability and low cost of iron(III) complex **3**, as compared to the ruthenium porphyrin **5**, make it a potentially useful reagent for biomimetic catalytic transformations.



Scheme 3.2. Catalytic Oxidation of 2-*tert*-Butylanthracene (**8**) to 2-*tert*-Butylanthraquinone (**9**) Using Oligomeric Iodosylbenzene Sulfate (**2**) as the Oxidant.

In order to demonstrate the general character of the optimized reaction conditions, the oxidation of 2-*tert*-butylanthracene **8** using oxidant **2** in the presence of the Fe(III) phthalocyanine complex **3** (Scheme 3.2) was performed. Compared to the oxidation of anthracene **6**, the reaction of 2-*tert*-butylanthracene **8** was slower, probably due to steric hindrance caused by the *tert*-butyl group, with a 100% conversion reached only after 20 hours at room temperature. The GC analysis of the reaction mixture indicated the presence of a single product of oxidation, 2-*tert*-butylanthraquinone **9**, along with iodobenzene, resulting from the reduction of reagent **2**. 2-*tert*-Butylanthraquinone **9** was isolated from the reaction mixture by preparative column chromatography on silica gel as yellow needles in 72% yield and identified by comparison with an authentic sample.⁴⁵

In summary, the results of the study show that IBX-ester **1** and oligomeric iodosylbenzene sulfate **2** are efficient oxygenating agents in the biomimetic catalytic

oxidation of aromatic hydrocarbons in the presence of metal porphyrin or phthalocyanine complexes. These two reagents can be used as safe and convenient alternatives to the potentially explosive iodosylbenzene. Reagents **1** and **2** can be conveniently prepared from common precursors and in contrast to the thermally unstable iodosylbenzene, they can be stored for extended periods at room temperature and are not explosive.

Chapter 4

Binuclear Iron (III) Phthalocyanine(μ -Oxodimer) Catalyzed Oxygenation of Aromatic Hydrocarbons with Tetra-*n*-butylammonium Oxone

4.1 Introduction

In chapters two and three of this thesis it has been shown that μ -oxobis[iron(III)-2,9(10),16(17),23(24)-tetra-*tert*-butylphthalocyanine] **1** is catalytically active towards alcohol oxidations and C-H bond activation oxidations. The disadvantage of using the hypervalent iodine reagents that were demonstrated in the first two chapters is the oxidant's low to moderate solubility in the corresponding organic solvent used in the reaction. To overcome this problem, tetra-*n*-butylammonium oxone was prepared and used as a highly soluble oxidant with iron μ -oxo dimer phthalocyanine **1** as the catalyst in the oxidation of many substrates.

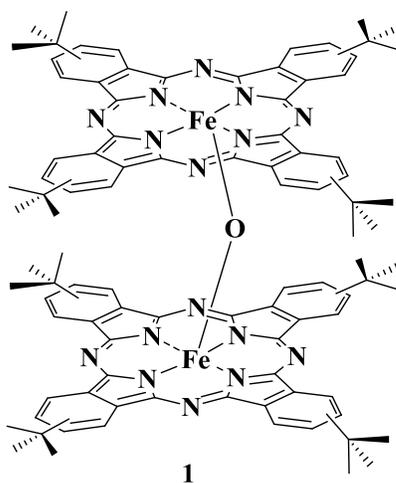


Figure 4.1. Iron(III) Phthalocyanine μ -oxo dimer (**1**)

Tetrabutylammonium oxone has been used in the epoxidation of alkenes. In these epoxidation reactions, manganese and iron *meso*-substituted porphyrins were used as catalysts.⁴⁶ In this chapter preliminary results for the oxidation of aromatic hydrocarbons by an iron μ -oxo dimer phthalocyanine/tetrabutylammonium oxone catalyst oxidant combination will be presented.

4.2 Experimental Setup

All reactions were performed under a dry nitrogen atmosphere with flame-dried glassware. Dichloromethane was distilled from CaH_2 and stored over molecular sieves (4 Å). Tetrabutylammonium oxone and iron μ -oxo dimer phthalocyanine **1** were prepared by previously reported methods.^{47,49} GC-MS analysis was carried out with an HP 5890 A Gas Chromatograph using a 5970 Series mass selective detector.

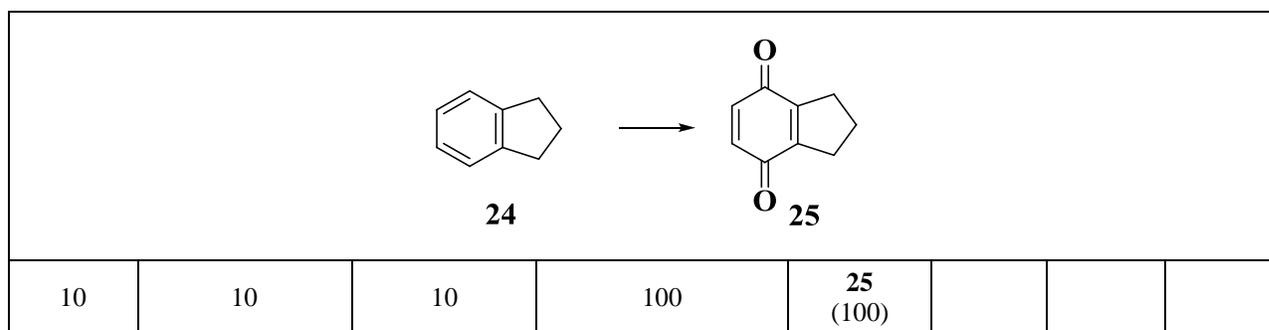
The following is the typical procedure used for the catalytic oxidation of substrates. A solution of the appropriate substrate (0.05 mmol) in dichloromethane (5 mL) was mixed with iron μ -oxo dimer phthalocyanine **1** (5 molar percent as compared to the substrate) and tetrabutylammonium oxone (6 equiv. of O), with stirring, at room temperature. Samples of the reaction mixture (100 μL) were collected every 30 min, filtered through 2–3 cm of silica gel suspended in a Pasteur pipet, washed with a mixture of ethyl acetate and hexane (2:3 v:v), and then analyzed using GC-MS.

4.3 Results and Discussion

Table 4.1. Catalytic Oxidations with Iron Phthalocyanine μ -oxo Dimer (1)

Entry	Catalyst (Mol. %)	Time (min)	Conversion (isolated yield), %	Products Distribution (%)			
<p style="text-align: center;"> <chem>C1=CC=C2C=CC=CC2=C1</chem> \longrightarrow <chem>O=C1C=CC(=O)C=C1</chem> 2 3 </p>							
1	none	2880	11	3 (100)			
2	5	5	100	3 (100)			
3	5 ^a	30	45	3 (100)			
<p style="text-align: center;"> <chem>CC(C)(C)c1ccc2cc3ccccc3cc2c1</chem> \longrightarrow <chem>CC(C)(C)c1ccc(O)c2ccccc12</chem> + <chem>CC(C)(C)c1ccc2c(=O)c3ccccc3c(=O)c21</chem> + <chem>CC(C)(C)c1ccc2c(=O)c3cc(O)c(=O)c3cc21</chem> 4 5 6 7 </p>							
4	5	10	100	5 (1)	6 (97)	7 (2)	
<p style="text-align: center;"> <chem>Cc1ccc2cc3ccccc3cc2c1</chem> \longrightarrow <chem>O=C1C=CC(=O)C=C1C</chem> + <chem>O=C1C=CC(=O)C=C1</chem> + <chem>O=C1C=CC(O)C(=O)C=C1C</chem> + <chem>O=C1C=CC(O)C(=O)C=C1</chem> 8 9 10 11 12 </p>							
5	5	5	100	9 (47)	10 (47)	11 (4)	12 (2)

6	5	10	58	14 (41)	15 (42)	16 (2)	17 (15)
7	5	10	100	19 (100)			
8	5	30	90	21 (100)			
9	5	10	100	23 (100)			



- a) 5,10,15,20-Tetrakis(pentafluorophenyl)-21H,23H-porphyrin iron(III) chloride was used as the catalyst

We have investigated the catalytic oxidation of several hydrocarbons to their corresponding quinones. According to the GC-MS data, the reaction products shown in Table 4.1 were the only products formed under these reaction conditions.

Dichloromethane was chosen as the solvent for the reactions because the oxidant and catalyst are very soluble in it.

The first catalytic reaction that was performed with the Tetrabutylammonium oxone/ Iron Phthalocyanine μ -oxo Dimer **1** oxidant/catalyst pairing was the oxidation of anthracene **2** to anthracene-9,10-dione **3**. A 100% conversion was observed in 5 minutes when 5% molar equivalence of the iron phthalocyanine μ -oxo dimer **1** was used (entry 2). When employing a 5% molar equivalence of 5,10,15,20-tetrakis(pentafluorophenyl)-21H,23H-porphyrin iron(III) chloride as the catalyst only a 45% conversion in 30 minutes was observed (entry 3). Without the use of a catalyst only an 11% conversion was detected in 48 hours (entry 1).

The catalytic oxidation reaction of sterically crowded 2-*tert*-butylanthracene **4** gave a 100% conversion of the substrate to 2-*tert*-butylanthracene-9,10-dione **6**, as the

major product, in 5 minutes (entry 4). Though two other oxidation products were observed, 2-*tert*-butylanthracen-9-ol **5** and 6-*tert*-butyl-1-hydroxyanthracene-9,10-dione **6**, they only contributed 3% to the final product distribution.

In 5 minutes a 100% oxidation of 2-methylnaphthalene was observed with two well documented position isomers, 6-methylnaphthalene-1,4-dione **9** and 2-methylnaphthalene-1,4-dione **10**, as the main products (entry 4). Two other oxidation products, 5-hydroxy-6-methylnaphthalene-1,4-dione **11** and 8-hydroxy-2-methylnaphthalene-1,4-dione **12**, were detected, but only contributed 6% to the final oxidation product distribution.

The catalytic oxidation reaction of adamantane **13** gave a 58% conversion in 10 minutes (entry 5). The main two oxidation products were 1-adamantanol **14** and 2-Adamantone **15**. 1-hydroxy-2-adamantanone **16** and a rearrangement product **17** were two minor products that were also observed. This result demonstrates that the Tetrabutylammonium oxone/Iron Phthalocyanine μ -oxo Dimer **1** oxidant/catalyst pairing is active towards aliphatic hydrogens as well.

The catalytic oxidation reaction of 9,10-dihydroanthracene **8** to anthracene-9,10-dione **9** in 10 minutes with a 100% conversion (entry 7) was further evidence for the ability of the catalyst/oxidant pair to activate aliphatic carbon hydrogen bonds. As expected, if aromatic and aliphatic carbon hydrogen bonds were present in a molecule, the oxidation occurred at the aromatic carbon hydrogen bonds. This was shown in the reactions of ethylbenzene **20** to 2-ethylcyclohexa-2,5-diene-1,4-dione **21**, 1,2,3,4-tetrahydronaphthalene **22** to 5,6,7,8-tetrahydronaphthalene-1,4-dione **23**, and 2,3-

dihydro-1H-indene **24** to 2,3-dihydro-1H-indene-4,7-dione **25**, with a 100% conversion in 10 minutes for 1,2,3,4-tetrahydronaphthalene **22** and 2,3-dihydro-1H-indene **24** and a 90% conversion in 30 minutes for ethylbenzene **20** (entries 8-10).

In summary, preliminary results for the new iron μ -oxo dimer phthalocyanine/tetrabutylammonium oxone catalyst oxidant combination were presented. The catalyst oxidation pair produced very efficient oxidations of multiple substrates with selective oxidations of aromatic carbon hydrogen bonds over aliphatic bonds. Further studies will be conducted to determine the isolated yields for the reactions presented.

agent,⁵³ which has also found widespread application in various transition metal porphyrin catalyzed oxygenation reactions.⁵⁴ Despite its usefulness as an oxidant, practical applications of iodosylbenzene are overshadowed by its low solubility,⁵³ low thermal stability, and explosive properties upon heating.⁵⁵ We have recently shown that the μ -oxobis[iron(III)-2,9(10),16(17),23(24)-tetra-tert-butylphthalocyanine] **3** is an effective catalyst for the oxidation of a variety of organic substrates with hypervalent iodine reagents.⁵⁶ In particular, the oligomeric iodosylbenzene sulfate $[(\text{PhIO})_3\text{SO}_3]_n$ **2** was proven to be an excellent alternative to iodosylbenzene in transition metal phthalocyanine- and porphyrin-catalyzed reactions.

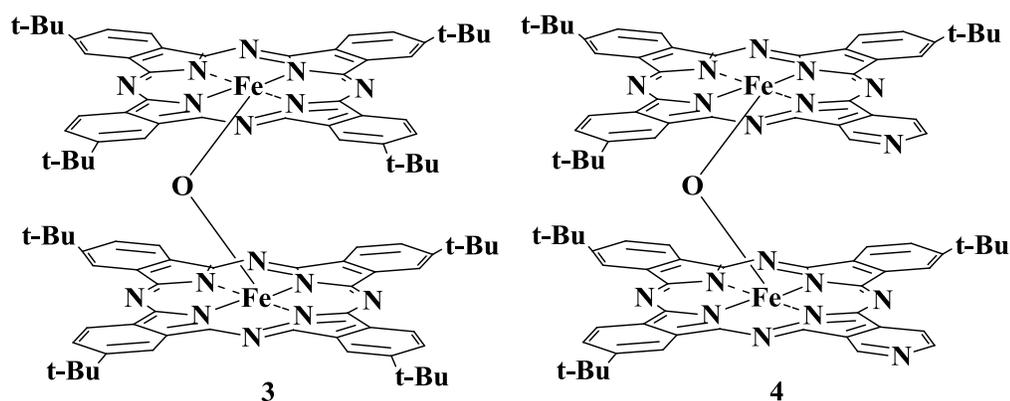
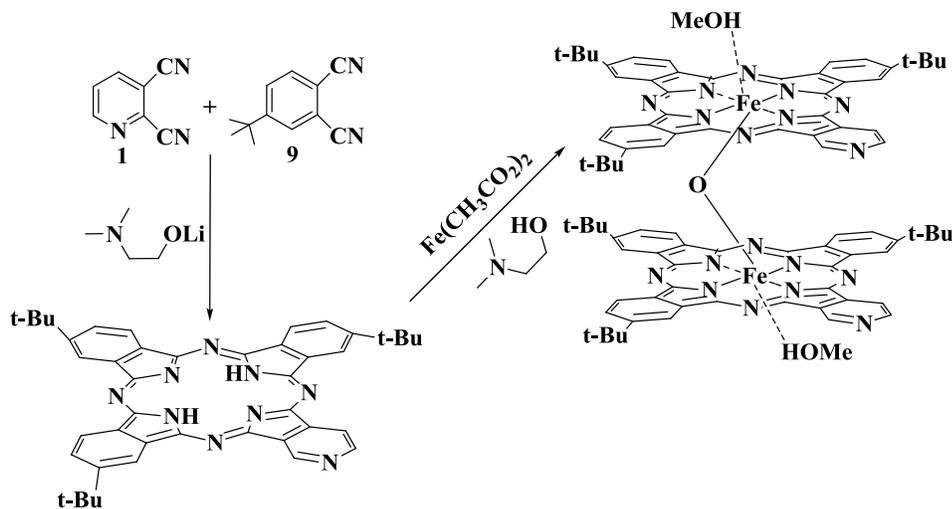


Figure 5.2. Iron(III) Phthalocyanine μ -oxo Dimers (**3**) and (**4**)

In this chapter, results on comparative reactivity of the well-known compound **3** and new iron(III) phthalocyanine m-oxodimer **4** (Figure 5.2) in the biomimetic oxidation of several aromatic compounds using traditional iodosylbenzene **1** and the new hypervalent iodine reagent **2** (Figure 5.1) as terminal oxidants will be reported.

5.2 Experimental Setup

All reactions were performed under a dry nitrogen atmosphere with flame-dried glassware. All commercial reagents were ACS reagent grade and used without further purification. Toluene and dichloromethane were distilled from CaH₂ and stored over molecular sieves. Catalyst **3**,⁵⁷ iodosylbenzene sulfate **2**^{56,58} and iodosylbenzene **1**^{50a} were prepared by known methods. GC-MS analysis was carried out with an HP 5890 A Gas Chromatograph using a 5970 Series mass selective detector. The APCI-MS experiment was conducted using a Finnegan LCQ LC-MS system. NMR spectra were recorded on a Varian INOVA instrument with 500 MHz frequency for protons. Chemical shifts are reported in parts per million and referenced to TMS as an internal standard. UV-vis spectra were collected on Jasco V-730 spectrophotometers. MCD spectra were acquired on an OLIS DCM-17 system with a 1.4T DeSa permanent magnet.



Scheme 5.1. Synthetic Pathway for Preparation of the Iron(III) Phthalocyanine μ -oxo Dimer (**4**)

The preparation of catalyst **4** is shown in Scheme 5.1. The asymmetrical metal-free phthalocyanine precursor was synthesized according to the previously reported procedure.⁵⁹ Selected data for this compound are: APCI-MS: $m/z = 684 [M+1]^+$ 100%; UV-vis (CHCl_3): $\lambda = 342, 605, 634, 659, 685 \text{ nm}$.

The preparation of μ -oxodimer from the asymmetrical a metal-free precursor was achieved by the reaction between 0.54 g (0.79 mmol, 1 equiv.) of metal-free phthalocyanine and 1.37 g (7.9 mmol, 10 equiv.) of iron(II) acetate in 5 mL of boiling N,N-dimethyl ethanolamine for 8 h under an argon atmosphere. After this period of time, the reaction mixture was poured into water saturated with sodium chloride and the reaction product was filtered. The target complex **4** was purified using basic alumina (Sorbent Technologies, Act. 1, 50–200 mm). First, toluene was used as the eluent to remove reaction impurities and unreacted asymmetrical metal-free phthalocyanine. After this, the target μ -oxodimer **4** was eluted by pure methanol. The methanol was evaporated under reduced pressure and the product was finally purified by washing with hexane and recrystallization from methanol/hexane.; yield: 31%; UV-Vis and MCD spectra of **4** are shown in Figure 5.3, while its APCI-mass spectrum is presented in Figure 4.4. Selected data for this compound are: UV-Vis (toluene): $\lambda (\log e) = 358 (4.83), 560 \text{ sh}, 633 \text{ sh}, 667 \text{ sh}, 700 \text{ nm} (4.9)$; APCI-MS: $m/z = 1491 [M+1]^+$ 100%, $1522 [M+\text{CH}_3\text{OH}]^+$ 50%, $1554 [M+2\text{CH}_3\text{OH}]^+$.

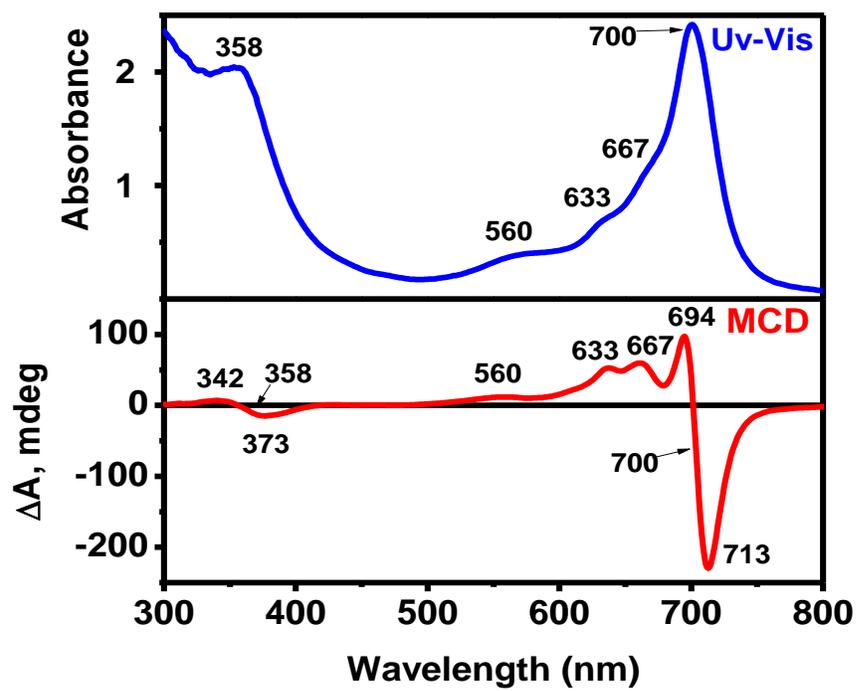


Figure 5.3. UV-vis (top) and MCD (bottom) Spectra of Iron(III) Phthalocyanine μ -oxo Dimer (**4**)

VN_090709100142 #69-76 RT: 0.65-0.72 AV: 8 NL: 2.16E8
T: + c APCI corona Full ms [150.00-2000.00]

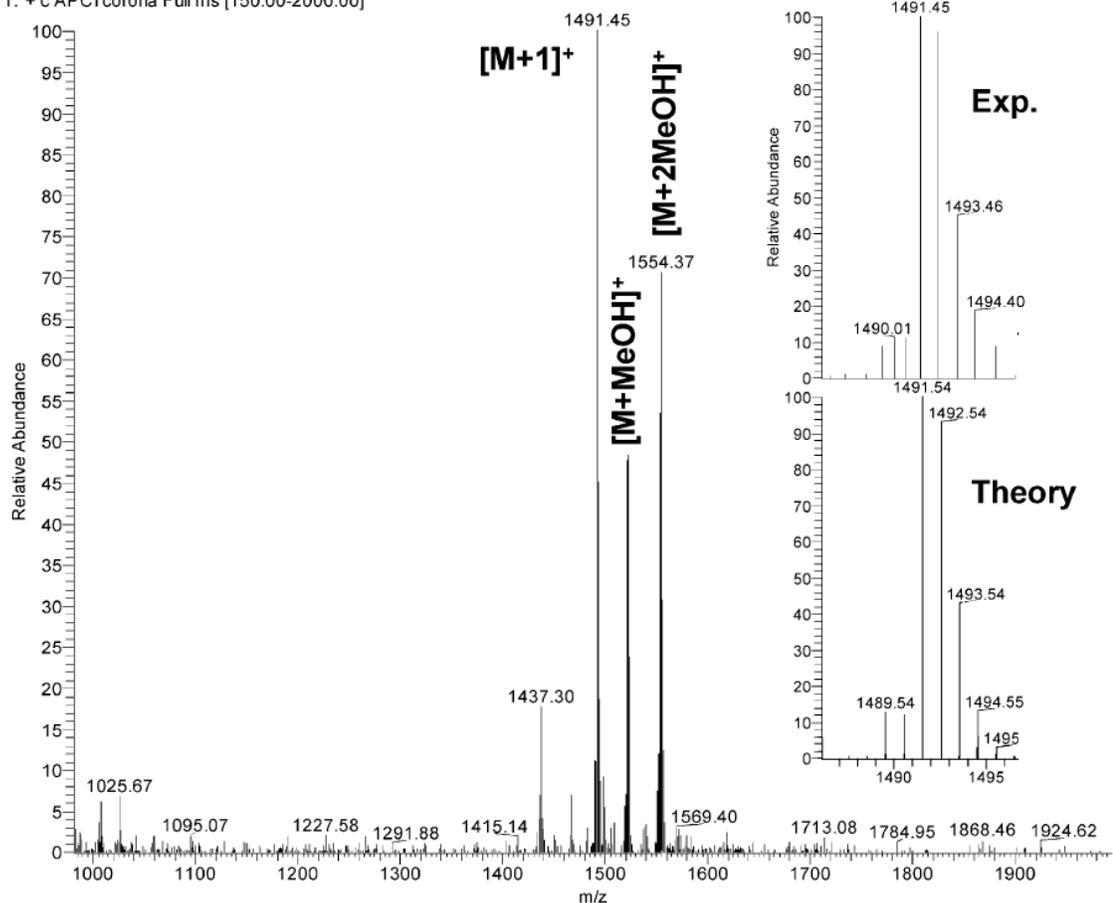


Figure 5.4. APCI MS of the Iron(III) Phthalocyanin μ -oxo Dimer (**4**).

The presence of one or two methanol molecules in **4** was further confirmed by an APCI MS/MS method on the 1554 $[M+2CH_3OH]^+$ peak; IR (KBr): $\nu=3068$ (Ar-H), 2958 (CH_3), 2925 (CH_3), 2856 (CH_3), 2364, 2345, 1609, 1500, 1482, 1388, 1364, 1327, 1257, 1197, 1082, 1027, 923, 900, 840, 750, 692 cm^{-1} .

The typical procedure used for catalytic oxidation of aromatic hydrocarbons follows. A solution of the appropriate hydrocarbon (0.056–0.070 mmol) in toluene or methanol (5–10 mL) was mixed with the amount of the catalyst **3** or **4** shown in Table

5.1. and the hypervalent iodine oxidant 1 or 2 (4.5–12 equiv. of O), with stirring, at the temperature indicated in Table 4.1. Samples of the reaction mixture (100 mL) were collected every 30 min, filtered through 2–3 cm of silica gel suspended in a Pasteur pipet, washed with a mixture of ethyl acetate and hexane (2:3 v:v), and then analyzed using GC-MS.

The procedure used for catalytic oxidation of phenanthrene follows. A solution of phenanthrene (25 mg, 0.140 mmol) in methanol (25 mL) was mixed with catalyst 4 (31 mg, 0.02 mmol) and the oxidant 2 (208 mg, 0.281 mmol) at room temperature. The reaction mixture (100 mL samples) was analyzed using GC-MS every 30 min. Upon completion of the reaction, the reaction mixture was concentrated and products were separated using a TLC plate and ethyl acetate/hexane (2:3 v:v) mixture as the eluent. Reaction products were collected as separate fractions and analyzed by GC-MS, ^1H and COSY NMR methods.

Phenanthrene-9,10-dione: Yield: 1.2 mg (4.1%); GC-MS: $m/z = 208$ (M) $^+$; ^1H NMR (500 MHz, CDCl_3): $\delta=8.21$ (d, $J = 7.5$ Hz, 1.5 Hz, 2 H), 8.02 (d, $J = 8$ Hz, 2H), 7.73 (t, $J = 7.5$ Hz, 1.5 Hz, 2 H), 7.48 (t, $J = 8$ Hz, 2H).

4-Hydroxyphenanthrene-9,10-dione: Yield: 10.7 mg (34%); GC-MS: $m/z = 224$ (M) $^+$; ^1H NMR (500 MHz, CDCl_3): $\delta=7.93$ (d, $J = 7$ Hz, 1H), 7.87 (d, $J = 5.5$ Hz, 2.5 Hz, 2 H), 7.79 (d, $J = 7.5$ Hz, 1.5 Hz, 1 H), 7.64 (t, $J = 7.5$ Hz, 1.5 Hz, 1 H), 7.47 (t, $J = 8$ Hz, 1.5 Hz, 1 H), 7.40 (t, $J = 7$ Hz, 2H).

Phenanthrene-4,9,10-triol: Yield: 3.9 mg (12.3%); GCMS: $m/z = 226$ (M) $^+$; ^1H NMR (500 MHz, CDCl_3): $\delta = 7.83$ (m, 4 H), 7.50 (d, $J = 7.5$ Hz, 1 H), 7.3 (m, 2 H).

5.3 Results and Discussion

The oligomeric iodosylbenzene sulfate $[(\text{PhIO})_3 \cdot \text{SO}_3]_n$ **2** was prepared by simple treatment of commercially available (diacetoxyiodo)benzene with aqueous sodium hydrogen sulfate and isolated as a thermally stable, yellow, crystalline solid.⁵⁶ Complex **3** was prepared using a direct high-temperature reaction between 4-*tert*-butylphthalonitrile and iron(II) acetate as described previously,⁵⁷ while preparation of the new catalyst **4** is based on the metallation reaction of asymmetric metal-free μ -oxobis [iron(III)-pyridino-[3,4]-9(10),16(17),23(24)-tri-*tert*-butyl-tribenzoporphyrine] and is described in the Experimental Section. There are two main reasons for testing the catalyst **4**. First, the introduction of a fused pyridine ring into the phthalocyanine core increases its first oxidation potential. Second, the nitrogen atom of the pyridine ring can serve as an effective axial group, which can be coordinated to one iron(III) center, thus increasing the electron density on the second iron(III) ion in **4**.

The results of the catalytic oxidation of anthracene **5**, 2-*tert*-butylanthracene **8**, 2-methylnaphthalene **12**, 9,10-phenanthrene **16**, and adamantane **20** using hypervalent oxidants **1** and **2** and catalysts **3** and **4** are presented in Table 4.1. The use of iodosylbenzene and oxidant **2** in the first reaction in the presence of μ -oxo dimer **3** was previously reported in the literature.^{56b}

Table 5.1. Catalytic Oxidations of Aromatic Hydrocarbons and Adamantane Using Oxidants (1) and (2) and Catalysts (3) and (4).

Entry	Catalyst (Mol. %)	Oxidant (Mol. Eq.)	Solvent	T (°C)	Time (h)	Conversion (isolated yield), %	Products Distribution (%)		
<p style="text-align: center;"> <chem>c1ccc2cc3ccccc3cc2c1</chem> (5) \longrightarrow <chem>O=C1C=CC(=O)C=C1</chem> (6) + <chem>Oc1ccc2cc3ccccc3cc2c1=O</chem> (7) </p>									
1	none	2 (4.5)	MeOH	25	1	1.1	6 (100)		
2	none	2 (4.5)	MeOH	25	24	74	6 (48)	7 (52)	
3	Py (225)	2 (4.5)	MeOH	25	1	0.5	6 (100)		
4	Py (225)	2 (4.5)	MeOH	25	24	25	6 (59)	7 (41)	
5	Fe ³⁺ (100)*	2 (6)	MeOH	25	1	0.4		7 (100)	
6	Fe ³⁺ (100)*	2 (6)	MeOH	25	5	2.8		7 (100)	
7	3 (10)	1 (7.5)	toluene	25	5	100	6 (100)		
8	3 (10)	2 (7.5)	toluene	25	2 ^[56b]	100	6 (100)		
9	4 (10)	1 (12)	MeOH	25	2	100	6 (100)		
10	4 (15)	2 (6)	MeOH	25	2	100	6 (85)	7 (15)	
11	4 (15)	2 (6)	MeOH	0	2.5	100	6 (90)	7 (10)	
<p style="text-align: center;"> <chem>Cc1ccc2cc3ccccc3cc2c1</chem> (8) \longrightarrow <chem>Cc1ccc2cc3ccccc3cc2c1=O</chem> (9) + <chem>Oc1ccc2cc3ccccc3cc2c1=O</chem> (10) + <chem>Oc1ccc2cc3ccccc3cc2c1=O</chem> (11) </p>									
12	3 (15)	2 (6)	toluene	25	20 ^[56b] ₁	100 (72)	9 (100)		
13	4 (15)	2 (4.5)	MeOH	25	0.5	100	9 (76)	10 (13)	11 (11)

14	3 (30)	2 (6)	toluene	25	24	1.3	13 (55)	14 (45)	
15	4 (15)	2 (6)	MeOH	25	2	89	13 (32)	14 (26)	15 (42)
16	4 (30)	2 (4.5)	MeOH	0	3	87	13 (39)	14 (30)	15 (31)
17	4 (5)	2 (6)	MeOH	25	3	96	13 (33)	14 (10)	15 (57)
18	3 (15)	2 (6)	toluene	25	2.5	0			
19	3 (30)	2 (6)	toluene	25	4	2	17 (100)		
20	4 (15)	2 (6)	MeOH	25	2.5	82 (50.5)	17 (13)	18 (66)	19 (21)
21	4 (45)	2 (6)	MeOH	25	3.5	93		18 (59)	19 (41)
22	4 (30)	2 (6)	MeOH	0	4	44	17 (40)	18 (33)	19 (27)
23	4 (5)	2 (6)	MeOH	25	3	100	17 (11)	18 (84)	19 (5)
24	3 (15)	2 (6)	toluene	25	24	0			
25	3 (45)	2 (6)	toluene	25	24	1.8	21 (100)		
26	4 (15)	2 (6)	MeOH	25	24	2.4	21 (100)		
27	4 (30)	2 (6)	MeOH	0	24	0			

* Fe(III) acetate was used as a source of the Fe(III) ions.

According to the GC-MS and NMR data, iodobenzene resulting from the reduction of hypervalent iodine reagents and reaction products shown in Table 5.1 were the only products formed under these reaction conditions. Methanol was found to be the best solvent for the oxidations in the presence of μ -oxo dimer **4**, while toluene was used for the reactions catalyzed by μ -oxo dimer **3** as previously discussed.⁵⁶

As was shown earlier,^{56b} the oxidation of anthracene with hypervalent iodine reagents **1** and **2** in the absence of catalysts at room temperature in toluene or at 40°C in dichloromethane proceeds extremely slowly and does not show any measurable conversion to anthraquinone **6** after 24 h. Reagent **2**, however, slowly oxidizes anthracene in methanol at room temperature with a 1% conversion after 1 hour and 74% conversion after 24 h (entries 1 and 2). It should be noted, however, that more reactive oxidant **2** leads to the formation of two reaction products after 24 h. The first one is the expected 9,10-anthraquinone **6**, while the second one is 1-hydroxy-9,10-anthraquinone **7**. The addition of 0.10–0.15 mol equiv of Fe(III)-phthalocyanines **3** and **4** leads to a significant increase in the reaction rate with a 100% conversion reached in 2–5 hours for catalyst **3** and 2 hours for catalyst **4** at room temperature (entries 7–10). In the case of catalyst **3** and catalyst **4**/oxidant **1** combination, (entries 7–9) the only reaction product observed in GC-MS was 9,10-anthraquinone, while in the case of catalyst **4**/oxidant **2** combination, 15% of the 1-hydroxy-9,10-anthraquinone was observed in the reaction mixture, suggesting that catalyst **4** can further oxygenate a less reactive (as compared to anthracene) 9,10-anthraquinone. Lowering the reaction temperature leads to a slightly slower conversion rate of the reaction in the presence of phthalocyanine **4**, but expectedly

results in a smaller amount of over-oxidized product **7** (entry 11). Since catalysts **3** and **4** degrade during catalytic oxidation reactions, and catalyst **4** has basic pyridine fragments in its core, the oxidation of the anthracene into anthraquinone was tested in the absence of catalysts but in the presence of pyridine (225 equiv.) or Fe(III) salt (100 equiv., entries 3–6). In both cases inhibition of the oxidation reaction was clearly observed.

In agreement with our previous reports, the data presented in Table 5.1 clearly indicate that the oligomeric iodosylbenzene sulfate **2** is the best oxidant, significantly more reactive than the commonly used iodosylbenzene, and thus this oxidant was used for the oxidation of the other aromatic compounds presented in Table 5.1.

The oxidation of the more sterically crowded *2-tert*-butylanthracene **8** is indicative of the superiority of catalyst **4** (entries 12 and 13). Indeed, with catalyst **3**, 100% conversion of **8** into *2-tert*-butyl-9,10-anthraquinone can be achieved after 20 hours (isolated yield is 72%), while complete oxidation of **8** with catalyst **4** was completed after 30 minutes. Similar to the oxidation of anthracene, small amounts of two additional over-oxidation products **10** and **11** were observed in the reaction mixture (entry 13).

The reasonable oxidation of 2-methylnaphthalene **12** to provitamin K can also be achieved only with the more active catalyst **4** (entries 14–17). Formation of three quinone products **13–15** was observed at 25 and 0°C. In the reaction at room temperature, the over-oxidized quinone **15** is the major reaction product (entries 15 and 17), while lowering the reaction temperature to 0°C leads to formation of the target quinone **13** as the major reaction product (entry 16).

Catalyst **3** is also not effective in the oxidation of phenanthrene into 5,6-phenanthrenedione **17** at room temperature (entries 18 and 19), while use of catalyst **4** leads to formation of the products **17–19**, which were isolated and characterized by NMR spectroscopy (entries 20–23). Expectedly, longer reaction times for room temperature oxidations favor over-oxidation products **18** and **19** (entries 20, 21, 23), while lowering the reaction temperature results in formation of **17** as the major reaction product. Finally, both catalysts **3** and **4** are not very effective in the oxidation of the adamantane into 1-adamantanol (entries 24–27) at 25 and 0°C.

In summary, the results of the study show that the oligomeric iodosylbenzene sulfate **2**/complex **4** combination is an efficient oxygenating pair in the biomimetic catalytic oxidation of aromatic hydrocarbons. New asymmetric μ -oxo dimer **4** is a significantly more powerful catalyst as compared to the well-known μ -oxo dimer **3** and can catalyze the oxidation of various aromatic substrates.

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Chapter 2

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