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β-Fluorinated Porphyrins and Related Compounds: An Overview

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Apart from a few examples, β-(poly)fluorinated and β-(poly)-perfluoroalkylated porphyrins were practically unknown until recently. In particular, β-octafluoro-*meso*-tetraarylporphyrins remained elusive ligands owing to the lack of any convenient access. The aim of this microreview is to highlight recent progress in the synthesis and characterization of β-fluoroporphyrins and β-(perfluoroalkyl)porphyrins, two new classes of so-called electron-deficient porphyrins.

1. Introduction

The last few decades have seen considerable advances in the design and study of synthetic porphyrins.[1] Reasons for this unfailing interest mainly lie in the key role played by the unique 18π-electron (aromatic) macrocycle in biological systems containing hemes. Thus, an iron porphyrin moiety is a common prosthetic group in many metalloenzymes such as cytochrome P450-dependent mono-oxygenases which catalyze the oxidation of unactivated C–H bonds with only dioxygen and an electron source. In 1979, Groves et al. reported the ability of the iron(III) complex of 5,10,15,20-tetraphenylporphyrin [(TPP)FeCl] to mimic the catalytic activity of cytochrome P450 in mono-oxygenation reactions. In a model system using iodosylbenzene (PhIO) as the oxygen source, this metalloporphyrin catalyzed the epoxidation of cyclohexene and the hydroxylation of cyclohexane.[2] Nevertheless, this first-generation catalyst, consisting of an unsubstituted core-planar tetraphenylporphyrin, suffered from a severe drawback: rapid destruction by self-oxidation and, subsequently, low efficiency. Chang and Ebina showed that the efficiency and stability of the complexes [(TPP)Fe^{III}Cl] and [(TPP)Mn^{III}Cl] towards the oxidizing medium (PhIO) could be significantly improved by introducing at the *meso* positions pentafluorophenyl groups, giving rise to a set of second-generation catalysts. It was suggested that the enhanced electron-deficiency of the porphyrin would generate a more electrophilic metal–oxo intermediate.[3] High-turnover, high-yield alkene epoxidation and alkane hydroxylation were achieved by Traylor

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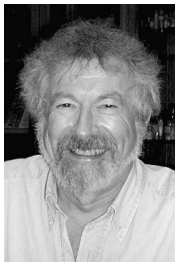
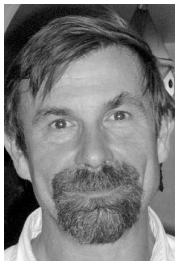


Jacques Leroy was born near Paris (France) in 1942 and studied chemistry at the Université Paris 6, where he received his Ph. D. degree in 1974 under the supervision of Prof. Jean Cantacuzène. The same year he was appointed as a CNRS researcher at the CERCOA near Paris in Dr. C. Wakselman's team. In 1994 he moved to the Ecole Normale Supérieure (Paris) to the research unit (UMR 8640) directed by Dr. C. Amatore. His studies have been mainly concerned with organofluorine chemistry. He has been particularly interested in fluorination methodology and in the synthesis of fluorinated heterocycles and the fluorinated analogues of natural products of biological interest. His current research interests focus on supramolecular chemistry and fluoroporphyrinoids.



Arnaud Bondon, born in 1960, studied Biochemistry and received his Ph. D. in Chemistry from the University of Rennes in 1987. After a postdoctoral stay, working on cytochrome P450 at Vanderbilt University with Prof. F. P. Guengerich, he returned to Dr. Simonneaux's group at the University of Rennes 1 as a Chargé de Recherche at the CNRS. He has been involved in the preparation and the evaluation of the catalytic activities of various β-fluorinated metalloporphyrins. Another area of his research has involved hemeproteins, performing a structural study of the active sites or electron-transfer analysis through NMR experiments. In particular he has focused his attention on the study of paramagnetic systems. In 2004 he set up a new team (RMN-Interactions Lipides Protéines) in a biological unit of the CNRS (UMR 6026) with the study of protein–lipid interactions as the main focus.

et al. with iron(III) porphyrins bearing 2,6-dichlorophenyl or pentachlorophenyl groups at the *meso* positions. The improvement observed was attributed both to the prevention of the formation of μ-oxo dimers by steric hindrance and to the slowing down of the rate of oxidative destruction due to the electronic effects of the *meso* substituents.[4] Nevertheless, despite the substantial improvements gained with second-generation catalysts, porphyrins with enhanced redox potentials, able to resist oxidative destruction and exhibiting a high efficiency, were still needed. Metal complexes of β-octahalogeno-*meso*-tetraarylporphyrins could in principle fulfill these criteria. The first use of such a catalyst was reported in 1987 by Traylor and Tsuchiya. The complex [2,3,7,8,12,13,17,18-octabromo-5,10,15,20-tetrakis(2,6-dichlorophenyl)porphinato]iron(III) chloride [(β-Br_8TDCPP)FeCl] was found to be remarkably stable towards destruction and efficient in the hydroxylation of norbornane in the presence of PhIO as compared with the β-hydrogenated counterpart [(TDCPP)FeCl].[5] This finding has spurred on extensive studies on third-generation porphyrins deriving from the second-generation ones by introducing a variable number of strong electron-withdrawing substituents such as halogens (see below), cyano,[6] or nitro[7] groups into the pyrrolic β positions. Besides mimicking the mono-oxygenation process in model systems such as the epoxidation of alkenes or the hydroxylation of alkanes and aromatic rings,[8] metalloporphyrins can mediate other hydrocarbon-functionalization reactions such as aziridination,[9] the cyclopropanation of alkenes,[9a,10] or the amidation of saturated C–H bonds.[9b,11] Moreover, porphyrins form a class of chromophores with a wide range of applications, for example, they have uses in photodynamic therapy (PDT),[12] multiporphyrin arrays,[13] and in various other material applications.[14] As a result of these efforts, a large number of sterically and electronically modified porphyrins have been reported. This microreview will focus mainly on genuine β-fluoroporphyrins and on a related class of highly "electron-deficient" ligands, β-(perfluoroalkyl)porphyrins. It intends to cover our own findings in the field as well as literature results. Apart from a few exceptions, *meso*-fluorination or -perfluoroalkylation will not be considered here.

2. β-Fluoroporphyrins

2.1 Direct β-Halogenation

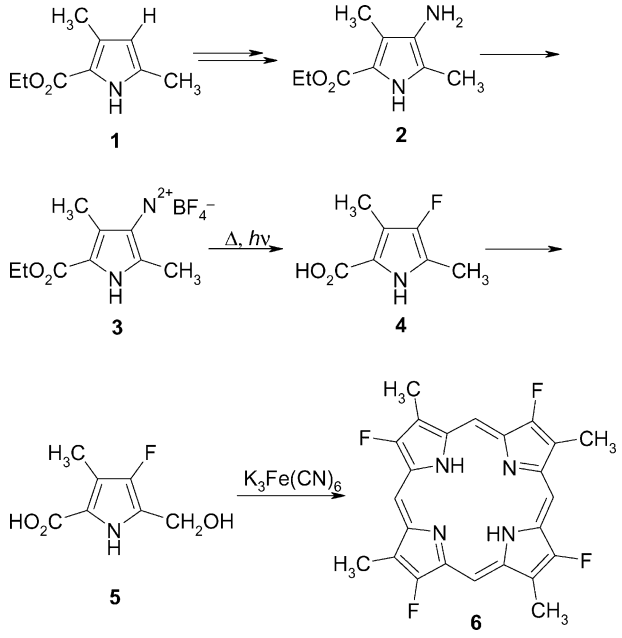
Until the two first reports on authentic β-octafluoro-*meso*-tetraarylporphyrins were published in 1997 by two independent groups,[15,16] most of the studies devoted to β-(poly)haloporphyrins were confined to the halogens bromine and chlorine.[17] Preparations of β-(poly)bromo- or β-(poly)chloroporphyrins generally involve the direct halogenation of a preformed free-base porphyrin or a metal derivative. For example, electrophilic bromination of (TPP)H_2 with *N*-bromosuccinimide (NBS) in refluxing chloroform led to a mixture of (β-Br_xTPP)H_2 (where x = 1–4).[18] Higher degrees of bromination (x = 5–8) could be reached by the reaction of various metalloporphyrins with NBS.[5,19] The porphyrin (β-Br_8TPP)H_2 has also been conveniently prepared by the reaction of bromine with [(TPP)Cu^{II}] and subsequent demetalation.[20a] Under these conditions, 5,10,15,20-tetrakis(3′,5′-dimethoxyphenyl)porphinato copper(II) was brominated at the eight β-pyrrole positions and at the eight *o*-phenyl positions.[20b] Similarly, β-octachlorination was accomplished with *N*-chlorosuccinimide (NCS) or chlorine, although extra chlorination of the *meso*-phenyl groups might also be observed.[19c,21d] For example, the porphyrin (β-Cl_8TPP)H_2 was obtained by the chlorination of the nickel(II) complex of (TPP)H_2 with NCS,[21a,21c] while the use of chlorine and $FeCl_3$ led to β-octachlorination of the complex [(TDCPP)FeCl].[21b] On the other hand, the zinc(II) complexes [(TDCPP)Zn], [(TPFPP)Zn] [{5,10,15,20-tetrakis(pentafluorophenyl)porphinato}Zn^{II}], or [(TPP)Zn] have been successfully β-octachlorinated by using NCS under irradiation.[19b] Recently, Senge et al. prepared in low yields the zinc(II) and nickel(II) complexes of 2,3,7,8,12,13,17,18-octachloroporphyrin by the reaction of 3,4-dichloro-1*H*-pyrrole with formaldehyde and *p*-toluenesulfonic acid (PTSA) catalysis followed by oxidation with Ag_2O. The very insoluble free-base porphyrin could neither be isolated nor characterized.[22]

By analogy with the bromination and chlorination reactions cited above, the direct fluorination of porphyrins with molecular fluorine was attractive, although fluorination of pyrrole gave only tars.[23] In 1989, Tsuchiya and Seno reported a preparation of [2,3,7,8,12,13,17,18-octafluoro-5,10,15,20-tetrakis(pentafluorophenyl)porphinato]iron(III) chloride [(β-F_8TPFPP)FeCl]: "The fluorination of pyrrole protons of Zn complex **3** was performed by cobalt fluoride in dichloromethane and N-containing aromatic solvent, or silver fluoride in dichloromethane",[24] where Zn complex **3** was [(TPFPP)Zn]. Besides the lack of any reproducible experimental details, identification of the purported β-octafluorinated compounds was minimal as well as erratic. In particular, the porphyrins [(β-F_8TPFPP)Zn] and (β-F_8TPFPP)H_2 had absorption spectra featuring redshifted Soret bands (at 441 and 430 nm, respectively) compared with their unfluorinated counterparts.[24] In contrast, we[15] and others[16] found that the authentic, fully characterized compounds display blueshifted Soret bands. In a patent, Ellis and Lyons mentioned the fluorination of the same zinc complex with dilute fluorine in the presence of trace amounts of cobalt fluoride or silver(II) fluoride.[25] Neither the experimental data nor the details of the characterization of the compound obtained were given. In our hands, attempted fluorination of [(TPFPP)Zn] with dilute fluorine (2% in nitrogen) at –10 °C in dichloromethane gave an intractable mixture. This approach was finally discarded to the benefit of an expectedly more controllable route, namely, an elaboration of the β-octafluorinated porphyrin macrocycle from a β-fluorinated pyrrole unit.

2.2 The First (Partially) β-Fluorinated Porphyrins

Up to 1997, the only reliable literature reports on β-fluoroporphyrins were those of the Ogoshi and Suzuki groups.

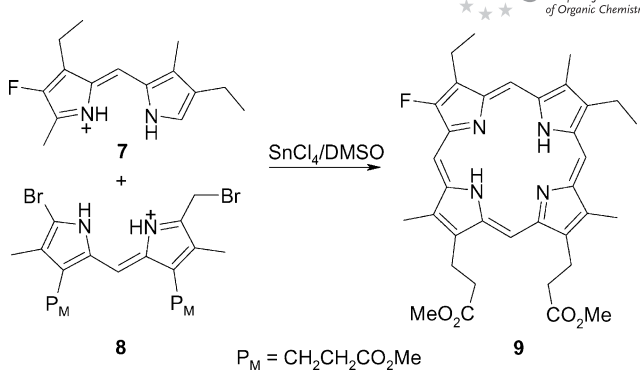
Ogoshi and co-workers prepared the first example of a ring-fluorinated porphyrin, 2,7,12,17-tetrafluoro-3,8,13,18-tetramethylporphyrin (**6**). This compound was obtained in 2% yield by tetramerization in the presence of potassium hexacyanoferrate(III) of 4-fluoro-5-hydroxymethyl-3-methylpyrrole-2-carboxylic acid (**5**) (Scheme 1). This latter was prepared from pyrrole **1** through a multistep sequence involving at the fluorination step a modified Schiemann reaction, that is, the photolysis of the pyrrole-β-diazonium tetrafluoroborate salt **3**.[26]



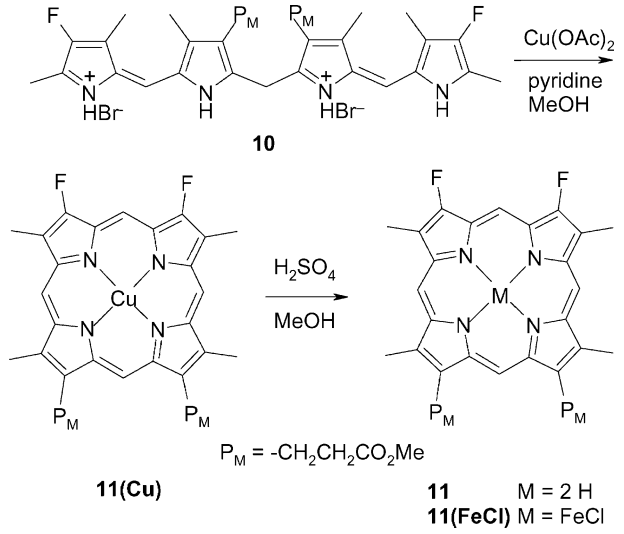
Scheme 1.

Suzuki et al.[27a] reported the total syntheses of 1-fluoro-1-demethylmesoporphyrin-IX (**9**) and its zinc(II) and iron(III) derivatives. This latter, after saponification of the ester groups, formed a stable reconstituted hemin with whale sperm apomyoglobin. The introduction of fluorine at a peripheral position served as a probe through the high- and low-spin states of the iron(III) complexes. The synthetic route to **9** involved a "2+2" condensation of two dipyrromethene units **7** and **8** (Scheme 2). The fluorinated dipyrromethene **7** was obtained by condensation (47% HBr in methanol) of 3-fluoro-2-methyl-4-ethylpyrrole with 2-formyl-3-methyl-4-ethylpyrrole. The fluoropyrrole was prepared by thermal decarboxylation of the 3-ethyl analogue of the acid **5**. Some other ring-monofluorinated porphyrins and iron(III) derivatives have been prepared following the same methodology.[27b]

Yamamoto and co-workers[28] synthesized the C_2-symmetric hemin [13,17-bis(2-methoxycarbonylethyl)-3,7-difluoro-2,8,12,18-tetramethylporphinato]iron(III) chloride [**11(FeCl)**] and incorporated it into sperm whale apomyoglobin (Mb) to investigate the effect of protein-induced rhombic perturbations on the electronic structure of the active site of myoglobin by using ^{19}F NMR spectroscopy. The synthetic route to this hemin involved the copper-mediated cyclization of the difluorobiladiene-*ac* **10**, prepared, inter alia, from 4-fluoro-2-formyl-3,5-dimethylpyrrole, into the intermediate copper(II) complex [**11(Cu)**] which was demetalated with concentrated sulfuric acid at 0 °C to give the free-base **11** (Scheme 3).



Scheme 2.



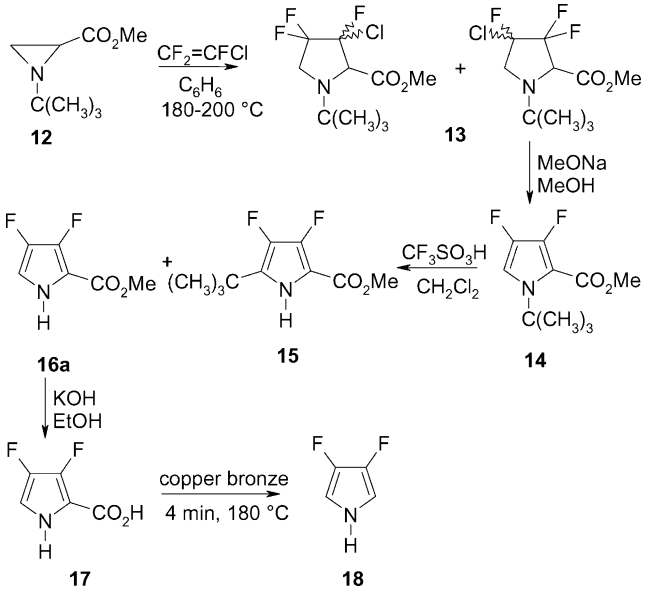
Scheme 3.

2.3 β-Octafluoroporphyrins

2.3.1 Synthesis of the Pyrrolic Precursors

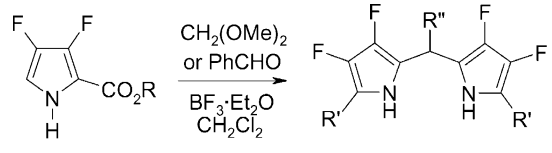
Since the feasibility of a direct β-octafluorination of a free-base porphyrin or a metalated derivative remained hypothetical, we looked for an elaboration of the porphyrin macrocycle by using a 3,4-difluoropyrrole unit. Although one fluorine atom could be introduced at a pyrrole β position by, for example, a Balz–Schiemann reaction,[26,27] introduction of a second fluorine at the β′ position was problematic. Based on our early work on the synthesis of various β-fluoropyrroles,[29] we reported in 1994 the first preparation of 3,4-difluoro-1*H*-pyrrole (**18**).[30] The first step of the synthetic route involved a [2+3] thermal cycloaddition of an *N*-protected aziridine **12** with chlorotrifluoroethylene (Scheme 4). A mixture of diastereo- and regioisomeric chlorofluoropyrrolidines **13** was obtained in acceptable yields (40–45%) despite harsh reaction conditions (heating at 180–

200 °C in an autoclave). Aromatization of the pyrrolidine mixture with sodium methoxide gave methyl 1-*tert*-butyl-3,4-difluoropyrrole-2-carboxylate (**14**) as the sole product. Subsequent dealkylation of the nitrogen atom with trifluoromethanesulfonic acid[31] afforded methyl 3,4-difluoro-1*H*-pyrrole-2-carboxylate (**16a**) (54–72% yield) along with the *C*-alkylated side-product, methyl 3,4-difluoro-5-*tert*-butyl-1*H*-pyrrole-2-carboxylate (**15**) (**16a**/**15** = 80:20 to 65:35). Saponification of the ester **16a** gave 3,4-difluoro-1*H*-pyrrole-2-carboxylic acid (**17**). Although 1-*tert*-butyl-3,4-difluoropyrrole-2-carboxylic acid was cleanly decarboxylated at 160 °C,[29b] heating the infusible acid **17** at the same temperature produced only a coal. Interestingly, 1-*tert*-butyl-3,4-difluoropyrrole remained unaffected on treatment with triflic acid, confirming the participation of the ester group of **14** in the dealkylation process. The reluctance of *N*-H pyrrolecarboxylic acids bearing electron-withdrawing substituents to undergo decarboxylation is well known. For example, 3,4-bis(trifluoromethyl)pyrrole-2-carboxylic[32a] and 4-(trifluoromethyl)pyrrole-3-carboxylic[32b] acids failed to decarboxylate on dry heating whether in the presence of copper powder or not. So we initially focused our attention on the method of Loader and co-workers for the decarboxylation of deactivated pyrrolecarboxylic acids.[32c] Their procedure used barium-promoted copper chromite as catalyst in quinoline at 200 °C and the volume of carbon dioxide evolved was monitored. When applied to the acid **17**, rapid decarboxylation occurred but recovery of 3,4-difluoro-1*H*-pyrrole (**18**) from the quinoline proved to be delicate owing to its low molecular weight and high vapor pressure. Clearly, this low-yielding procedure was unsuitable for this particular compound. In fact, simple flash-thermolysis of a mixture of **17** and copper-bronze powder at 180 °C in an evacuated stoppered glass tube afforded pure 3,4-difluoropyrrole (**18**) in 70–80% yields after purification by vacuum transfer (0.05 Torr) at room temperature into a cold (–70 °C) receiver.



Scheme 4.

Incidentally, the ester **16a** appeared to be a good substrate for the synthesis of symmetrical 1,9-unsubstituted β-tetrafluorodipyrromethanes. Such compounds are important building blocks for the rational synthesis of variously *meso*-substituted tetraarylporphyrins, for example, *trans*-A_2B_2, by the MacDonald-type "2+2" condensation route or related methods.[33] When methyl 3,4-difluoro-1*H*-pyrrole-2-carboxylate (**16a**) was treated with dimethoxymethane in CH_2Cl_2 at room temperature in the presence of boron trifluoride–diethyl ether ($BF_3{\cdot}Et_2O$), the corresponding 1,9-bis(methoxycarbonyl)-2,3,7,8-tetrafluorodipyrromethane (**19a**) formed sluggishly (ca. 72 h, 85% yield) (Scheme 5). The access to the desired 1,9-unsubstituted 2,3,7,8-tetrafluorodipyrromethane (**21**) required a thermal decarboxylation of the intermediate diacid **20**. As clean saponification of the methyl diester **19a** failed, the benzyl diester **19b** was prepared from pyrrole **16b** under the same conditions as dipyrromethane **19a** (56% yield), in view of its smooth debenzylation. None of the various methods tested was successful, for example, H_2/Pd-C, 1,4-cyclohexadiene/Pd-C, or $Et_3SiH/Pd(OAc)_2$. Since 5-aryl-substituted dipyrromethanes were more specifically required for the synthesis of, inter alia, β-octafluorinated *trans*-A_2B_2 porphyrins, the pyrrole **16a** was condensed with benzaldehyde under the same conditions to give 1,9-bis(methoxycarbonyl)-2,3,7,8-tetrafluoro-5-phenyldipyrromethane (**22**) (7 d at room temp., 60% yield). Again, clean preparation of the free diacid was unsuccessful.



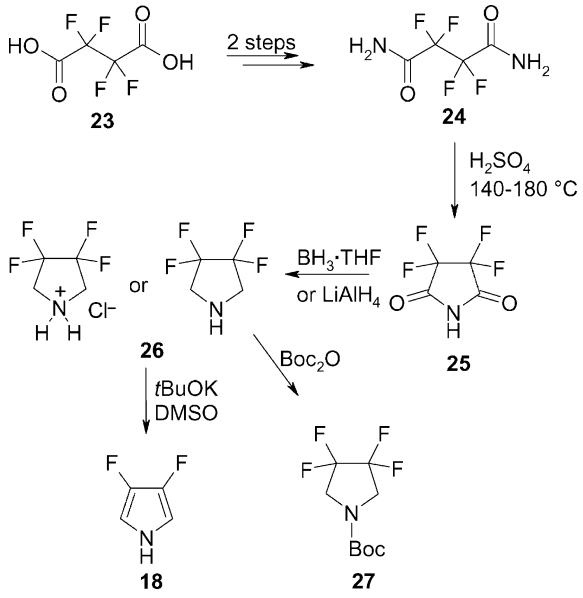
16a R = Me
16b R = CH_2Ph

19a R' = CO_2Me, R" = H
19b R' = CO_2CH_2Ph, R" = H
20 R' = CO_2H, R" = H
21 R' = R" = H
22 R' = CO_2Me, R" = Ph

Scheme 5.

In 1998, DiMagno and co-workers reported an alternative method for the synthesis of 3,4-difluoro-1*H*-pyrrole (**18**) starting from the commercially available tetrafluorosuccinic acid **23**.[34] The synthetic route is outlined in Scheme 6 and involves the dehydration/cyclization of 3,3,4,4-tetrafluorosuccinamide (**24**) into 3,3,4,4-tetrafluorosuccinimide (**25**). This latter was reduced to 3,3,4,4-tetrafluoropyrrolidine (**26**) either by lithium aluminium hydride in diethyl ether, giving the free-base, or by borane in THF, affording tetrafluoropyrrolidinium chloride after quenching by hydrogen chloride. The last step leading to 3,4-difluoropyrrole (**18**) implied a double H–F elimination and proved to be delicate. During our own study of this route 15 years ago we failed to aromatize the pyrrolidine **26** or its *N*-Boc derivative **27**, for example, with sodium methoxide in methanol. Many conditions to effect the H–F elimination,

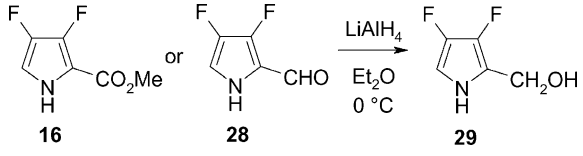
rendered difficult by the poor leaving-group ability of the fluoride ion and the nonactivation of protons in the 2 position (an E_{1cb}-like mechanism was invoked), have been surveyed.[34] Finally, a mixture of potassium *tert*-butoxide in DMSO appeared to be the best compromise in terms of handling, recovery, and yield (ca. 50%) considering the exceptional physical properties of 3,4-difluoropyrrole (**18**) which is a highly volatile, easily sublimating solid (m.p. 45 °C).[34]



Scheme 6.

2.3.2 Synthesis of β-Octafluoroporphyrins

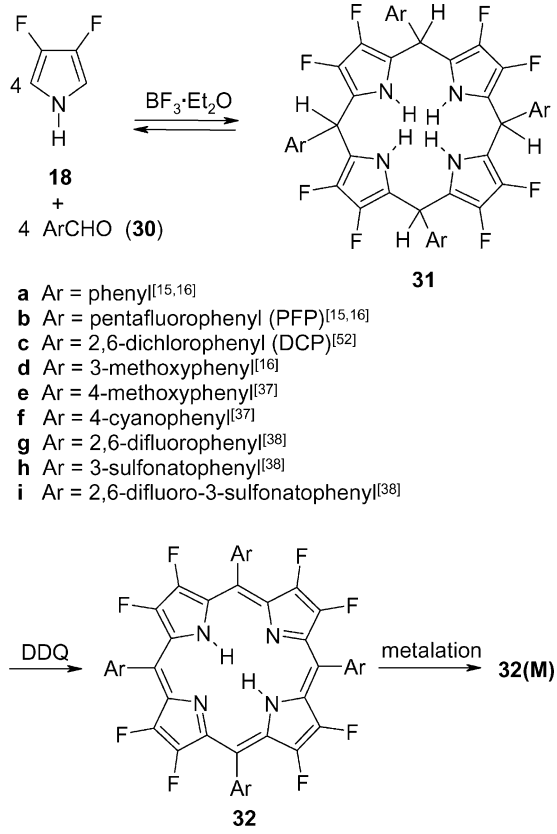
At the onset, we looked to synthesize the parent free-base 2,3,7,8,12,13,17,18-octafluoroporphyrin starting from the unstable 3,4-difluoro-2-(hydroxymethyl)pyrrole (**29**) obtained either by reduction of the ester **16** or by that of the aldehyde **28** with lithium aluminium hydride in diethyl ether (Scheme 7).



Scheme 7.

Attempts at the PTSA-catalyzed condensation/cyclization of pyrrole **29** with an excess of dimethoxymethane as a dehydrating agent and subsequent oxidation of the intermediate octafluoroporphyrinogen with *o*-chloranil were unsuccessful. Nevertheless, the presence of the porphyrinogen was detected once by mass spectrometry but this result was irreproducible.[35] Faced with these deceptive results, the synthesis of β-octafluoroporphyrins bearing *meso*-tetraaryl substituents was undertaken, starting from 3,4-difluoropyrrole (**18**) and following the two-step one-flask procedure described by Lindsey et al.[36]

We[15] and Woller and DiMagno[16] simultaneously reported the first synthesis of such β-octafluoro-*meso*-tetraarylporphyrins by using around 10^{-2} M solutions of 3,4-difluoropyrrole (**18**) and the corresponding aryl aldehyde **30** in dichloromethane at room temperature with $BF_3{\cdot}Et_2O$ as catalyst (ca. 10^{-3} M to stoichiometric). The first β-octafluoro-*meso*-tetraphenylporphyrin we isolated, (β-F_8TPP)-H_2 (**32a**), was prepared from benzaldehyde and 3,4-difluoropyrrole (**18**). The corresponding β-octafluoroporphyrinogen (**31a**) formed reversibly was identified by mass spectrometry (CI+NH_3) and was irreversibly oxidized by 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ) into 2,3,7,8,12,13,17,18-octafluoro-5,10,15,20-tetraphenylporphyrin (**32a**). Other representative examples were obtained by following the same procedure (see Scheme 8).[37,38] Yields were in the range 15–40%, generally close to those obtained when condensing pyrrole with the same aldehydes. The two water-soluble, free-base porphyrins **32h** and **32i** were prepared in good yields by sulfonation in heated fuming sulfuric acid of the porphyrins **32a** and **32g**, respectively. No detectable quantity of partially sulfonated material was formed.[38] Metalation of the free-bases **32** was mostly accomplished by using standard conditions.



Scheme 8.

Although the Lindsey procedure has been widely used for the preparation of sensitive porphyrins, it suffers from some drawbacks, particularly the tedious purification steps by column chromatography owing to the large amount of quinone used as oxidant. We have reinvestigated this point

by using an electrochemical instead of a chemical oxidation of preformed porphyrinogens. Although catalytic amounts of DDQ were necessary in the case of pyrrole and 3-fluoro-1*H*-pyrrole (**34**) (see below), the porphyrinogen obtained by condensation of 3,4-difluoropyrrole (**18**) with benzaldehyde or pentafluorobenzaldehyde could be directly oxidized at 1.2–1.45 V vs. SCE without any mediator in a sulfuric methanolic medium. The total yields (from **18**) were close to those obtained under standard Lindsey conditions (21–41%).[39]

2.3.3 Solid-State Structures of β-Octafluoro-meso-tetraarylporphyrin Derivatives

Owing to the small radius of fluorine and by comparison with the crystal structure of β-octabromo- and β-octachloro-*meso*-tetraarylporphyrins[40] it might be anticipated that β-octafluoro-*meso*-tetraarylporphyrins would display a quasiplanar structure like the benchmark *meso*-tetraphenylporphyrin $(TPP)H_2$. This was confirmed by the X-ray crystal structure determination of 2,3,7,8,12,13,17,18-octafluoro-5,10,15,20-tetrakis(pentafluorophenyl)porphyrin,[41] $(\beta\text{-}F_8TPFPP)H_2$ (**32b**), (Figure 1) and its zinc(II) complex $[(\beta\text{-}F_8TPFPP)Zn]$[16] [**32b(Zn)**]. In contrast, the perhalogenated analogues $(\beta\text{-}Cl_8TPFPP)H_2$ and $(\beta\text{-}Br_8TPFPP)H_2$ and some of their metal complexes were found to display a substantial saddle distortion culminating in the bulky bromine.[19d,42] The same trend in planarity was also reported for the Co^{II}[43] and Rh^{III}[44] complexes of $(\beta\text{-}F_8TPFPP)H_2$, while the porphyrin ring of the perfluorinated platinum complex $[(\beta\text{-}F_8TPFPP)Pt^{II}]$ [**32b(Pt)**] exists in a slightly saddle-shaped conformation.[45] The X-ray crystal structures of the ruthenium complexes $[(\beta\text{-}F_8TPFPP)(CO)Ru^{II}]$ and $[(\beta\text{-}F_8TPFPP)(PPh_3)_2Ru^{II}]$ have been determined.[46] Although the first complex was essentially planar, appreciable puckering was observed in the second. The pentafluorophenyl groups are generally nearly orthogonal to the porphyrin core to relieve steric encumbrance between the C_6F_5 rings and the β-pyrrolic fluorine atoms at the porphyrin periphery.[16,41,45]

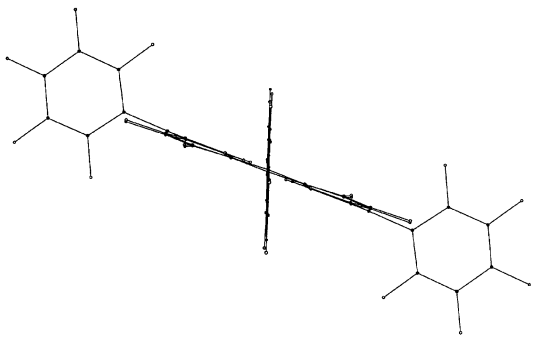


Figure 1. Edge-on view of $(\beta\text{-}F_8TPFPP)H_2$ (**32b**).

In stark contrast with most of the porphyrins cited above, the cores of the five coordinate zinc(II) complexes $[(\beta\text{-}F_8TPP)Zn(H_2O)]$[15] (Figure 2) and $[(\beta\text{-}F_8TPP)Zn(THF)]$[47] [**32a(Zn)**] were found to be extensively saddled with a superimposed smaller ruffling. The largest deviations from the porphyrin mean plane occurred at the β-pyrrolic carbon atoms (C_β) (0.59 Å for the aquo complex vs. 0.43 Å for the THF complex). It was assumed that dissimilarities in the solid-state distortions between the complexes $[(\beta\text{-}F_8TPP)Zn]$ and $[(\beta\text{-}F_8TPFPP)Zn]$ could originate in crystal packing forces and that these fluorinated porphyrins reside on shallow conformational potential energy surfaces.[15,47] Another possible explanation for the structural differences lies in the details of β-fluorine–aryl interactions related to the reversed quadrupolar charge distributions of the phenyl and perfluorophenyl substituents.[47]

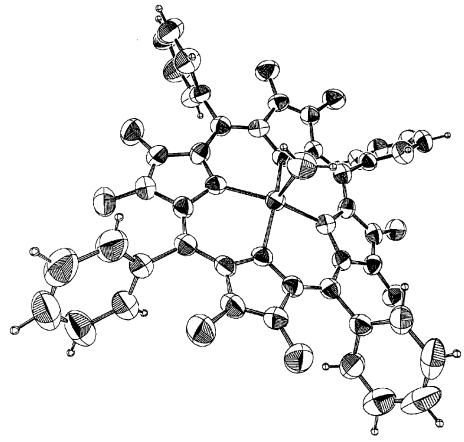


Figure 2. Perspective view of $[(\beta\text{-}F_8TPP)Zn(H_2O)]$ [**32a(Zn)**] (from ref.[15]).

2.3.4 Spectroscopic Properties of β-Octafluoro-meso-tetraarylporphyrins

The ^1H NMR spectra of the free-bases display upfield-shifted NH resonances in comparison to the unfluorinated counterparts, for example, –4.18 ppm for $(\beta\text{-}F_8TPP)H_2$ versus –2.79 ppm for $(TPP)H_2$.[15,16] This chemical shift reveals a solution structure in which highly symmetrical, planar porphyrins exhibit nonconjugated orthogonal aryl groups.[16] The free energy of activation $\Delta G^{\neq}$ for NH tautomerism of $(\beta\text{-}F_8TPP)H_2$ was estimated by ^{19}F NMR variable-temperature experiments to be around 13 kcal mol^{-1} compared with around 12 kcal mol^{-1} for $(TPP)H_2$.[15,16] This discrepancy has been attributed, inter alia, to a decreased basicity of the nitrogen sp^2 orbitals and a contraction of the NH bond in the inner-sphere proton transfer.[16]

Remarkably, β-octafluorination of *meso*-tetraarylporphyrins resulted in large hypsochromic shifts of the electronic absorption spectra relative to its unfluorinated counterparts, particularly in the Soret (B) band region. The lowest-energy (Q) bands were also hypsochromically shifted compared with the corresponding bands of TPPs (free-bases and metal complexes). Some selected values are listed in Table 1. This effect was observed for the free-bases (entries 2 and 4) as well as for their metal complexes (entries 6 and 8). In addition, the B(0,0)-Q(0,0) spectral splitting is particularly large, decreasing in the order $(\beta\text{-}F_8TPFPP)X > (\beta\text{-}F_8TPP)X > (TPP)X$ (where X = H_2, Zn,[16] or Pt[45]). The shifts of the absorption bands to higher energy were

attributed to the π-electron donation from the β-fluorines destabilizing the e_g LUMO orbitals in Gouterman's four-orbital model. The increased orthogonality of the aryl rings was thought to also contribute to the blueshift by minimizing the conjugative interactions at the *meso* positions.[47] In contrast, the introduction of chlorine or bromine atoms into the peripheral positions of the porphyrin macrocycle resulted in large bathochromic shifts of the electronic absorption spectra commonly associated with severe nonplanar distortions usually studied only in the solid state. Distortion destabilizes the HOMOs more than the LUMOs and the HOMO–LUMO gap is narrowed. Conversely, the incorporation of nonconjugated electron-withdrawing groups such as halides at the β-pyrrolic positions stabilizes the HOMOs and the LUMOs to roughly the same extent, regardless of the conformational consequences of the substitution.[48,49] Nonetheless, the widely accepted cause-and-effect relationship between nonplanarity and bathochromic spectral shifts remained in question.[50] In the case of the sterically encumbered porphyrins [(β-F_8TPP)Zn] and [(β-F_8TPFPP)Zn] displaying clear structural differences in the solid state, the optical spectra of crystalline (β-F_8TPP)H_2 (**32a**), [(β-F_8TPP)Zn] [**32a(Zn)**], (β-F_8TPFPP)H_2 (**32b**), [(β-F_8TPFPP)Zn] [**32b(Zn)**], (TPP)H_2, and [(TPP)Zn] in a KBr pellet have been compared with the spectra of the same compound in solution.[49] Transfer to solution resulted in no discernibly different shifts of the optical absorption bands for the fluorinated porphyrins and finally no structural information could be drawn from a comparison of the optical absorption spectra alone. In contrast to similar ground-state absorption spectra, the steady-state emission data for **32a** and [**32a(Zn)**] showed large differences compared with those of **32b** and [**32b(Zn)**]. Although the two former compounds showed broad emission spectra and substantial absorption/emission Stokes shifts (544 and 701 cm^{-1}, respectively), indicating a substantial excited-state conformational reorganization, the two latter exhibited emission spectra with fine structures and small Stokes shifts (198 and 202 cm^{-1}, respectively), indicating no significant reorganization of nuclear coordinates in the excited states. The quantum yields of fluorescence of the β-octafluorinated compounds **32a** and **32b** and their Zn complexes were slightly diminished compared with those of (TPP)H_2 and [(TPP)Zn] but remained important for such extremely electron-deficient porphyrins. Fluorescence lifetimes were reduced compared with that of TPP. Nevertheless, the radiative lifetimes were long compared with other strongly electron-deficient porphyrins. Finally, from the structural data and the disparate excited-state behavior, it was assumed that octafluorinated porphyrins **32a** and [**32a(Zn)**] would adopt nonplanar ground-state solution conformations compared with planar for the perfluorinated **32b** and [**32b(Zn)**].[47]

Table 1. Selected UV/Vis data in CH_2Cl_2.

Entry	Compound	Soret band λ_{max} [nm]	Q bands λ_{max} [nm]
1	(TPP)H_2[a,c]	419	516, 550, 593, 651
2	(β-F_8TPP)H_2 (**32a**)[a,c]	404	500, 534, 581, 637
3	(TPFPP)H_2[b,c]	411	505, 582, 638
4	(β-F_8TPFPP)H_2[b,c] (**32b**)	392	493, 578, 633
5	[(TPP)Zn][b,c]	418	547, 584
6	[(β-F_8TPP)Zn][a,c] [**32a(Zn)**]	410	540, 577
7	[(TPFPP)Zn][b,c]	415	545, 578
8	(β-[F_8TPFPP)Zn][b,c] [**32b(Zn)**]	408	538

[a] From ref.[15] [b] From ref.[52] [c] See also ref.[16]

2.3.5 Electrochemical Behavior of β-Octafluoro-meso-tetraphenylporphyrins

The one-electron redox potentials of porphyrins often reflect the energy levels of the HOMOs and LUMOs of the complexes. In particular, the differences between the first oxidation and reduction potentials, neglecting solvation effects, give an indication of the energy of the first absorption band of the porphyrins, this transition being principally a HOMO-to-LUMO excitation.[20a,51] The variation in the oxidation (resp. reduction) potentials is related to the modifications of the energy levels of the HOMOs (resp. LUMOs). The redox potentials of the porphyrins **32a** and **32b** and their Zn^{II} complexes [**32a(Zn)**] and [**32b(Zn)**] have been measured by cyclic voltammetry (see Table 2).[16,52] The voltammograms of the free-bases and zinc derivatives exhibit four reversible waves, two in oxidation and two in reduction. The β-octafluorinated porphyrin **32a** displayed a first oxidation potential at +1.25 and at –0.88 V for the first reduction, corresponding to positive shifts of, respectively, 290 and 380 mV compared with (TPP)H_2.[52] Perfluorination of [(TPP)Zn] resulted in 900 and 700 mV positive shifts of these potentials.[16] In accordance with the lowering of the energy levels of both the HOMOs and the LUMOs due to β-fluorination, the porphyrin ring oxidation is rendered more difficult while reduction becomes easier when compared with the unfluorinated counterparts. This effect was also found for the platinum(II) complex [(β-F_8TPFPP)Pt]. Cyclic voltammetry showed no porphyrin-centered oxidation at potentials ≤1.5 V (vs. $Ag/AgNO_3$), demonstrating that this complex is more resistant to oxidation than [(TPFPP)Pt] ($E^{1}/_{2}$ = 1.33 V) and [(TPP)Pt] ($E^{1}/_{2}$ = 0.97 V). The porphyrin-centered reduction of [(β-F_8TPFPP)Pt] occurred at –0.75 and –1.18 V, that is, anodically shifted compared with the reductions at –1.06 and –1.55 V for [(TPFPP)Pt] and at –1.51 V for [(TPP)Pt], respectively.[45]

Table 2. Selected electrochemical data in CH_2Cl_2 (V vs. SCE).[a]

Compound	$E^{+2/+1}$	$E^{+1/0}$	$E^{0/-1}$	$E^{-1/-2}$
(TPP)H_2	1.28	0.96	–1.26	–1.58
(β-F_8TPP)H_2 (**32a**)	1.62	1.25	–0.88	–1.11
[(TPP)Zn]	1.12	0.82	–1.39	–1.56
[(β-F_8TPP)Zn] [**32a(Zn)**]	1.24	1.12	–1.08	–1.34

[a] From ref.[52] See also ref.[16]

2.3.6 β-Octafluoro-meso-tetraphenylporphyrins in Catalysis

Synthetic metalloporphyrins have been widely studied as oxygenation catalysts in hydroxylations and epoxidations with various oxygen sources and different coordinating metals, for example, iron, manganese, or ruthenium. Owing to the high redox potentials measured for metalated β-octafluoro-*meso*-tetraarylporphyrins, it was anticipated that such complexes should offer resistance to oxidative decomposition and exhibit a very high efficiency in oxidation catalysis.

Iron Complexes: Bondon and co-workers reported the first use of β-octafluoro-*meso*-tetraphenylporphyrin iron(III) complexes as catalysts for mono-oxygenation reactions.[53] The pentacoordinate iron(III) complexes [(β-F_8TPP)FeCl] [**32a(FeCl)**], [(β-F_8TPFPP)FeCl] [**32b(FeCl)**], and [(β-F_8TDCPP)FeCl] [**32c(FeCl)**] were obtained from the corresponding free-bases with $FeCl_2{\cdot}4H_2O$ in refluxing DMF (Figure 3).

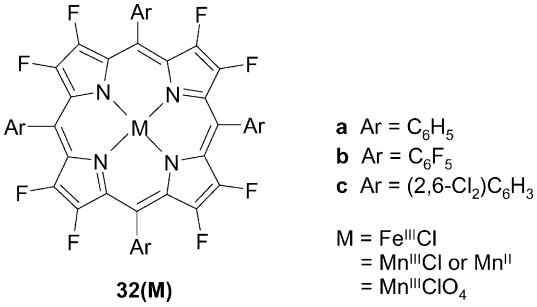


Figure 3. Metalated β-octafluoro-*meso*-tetraarylporphyrins used in catalysis.

The stability of iron porphyrins against oxidative degradation has been studied at room temperature under aerobic conditions with an oxidant-to-catalyst ratio of 100:1 by measuring the decrease of the Soret absorption band after 15 min. With PhIO, the introduction of fluorine resulted in a moderate improvement in stability for the two first porphyrins with respect to their unfluorinated counterparts. Although the complex [(TDCPP)FeCl] is known to be unusually stable,[3,54] its fluorinated analogue [**32c(FeCl)**] is partially decomposed. With hydrogen peroxide (H_2O_2), a decrease in stability upon β-fluorination is observed as compared with the hydrogenated analogues. The catalytic activity of the same iron porphyrins in hydroxylation and epoxidation reactions with PhIO and H_2O_2 has been evaluated. With PhIO, both cyclohexane and cyclooctene conversions are clearly improved with [**32a(FeCl)**] and [**32c(FeCl)**] despite the instability of these complexes towards the oxidant. With H_2O_2, the β-fluorination did not increase the efficiency of these catalysts which remained poorly active. Except for a very low activity observed with the complex [**32b(FeCl)**], none of the catalysts studied hydroxylated benzene.[53]

Manganese Complexes: β-Octafluorinated manganese(II) and (III) complexes have been prepared and assayed for catalysis (Figure 3).[55] The manganese complexes of the same fluorinated free-bases cited above were prepared by using $[Mn(OAc)_2{\cdot}4H_2O]$ in refluxing DMF. Pure [(β-F_8TPP)-Mn^{II}] [**32a(Mn)**] was obtained when the reaction was performed under anaerobic conditions, whereas manganese(II) complexes were always isolated even after prolonged refluxing under aerobic conditions with the β-F_8TPFPP and β-F_8TDCPP porphyrins. The complexes [(β-F_8TPFPP)-Mn^{II}] [**32b(Mn)**] and [(β-F_8TDCPP)Mn^{II}] [**32c(Mn)**] were stable in air in contrast to [**32a(Mn)**] which slowly oxidized in the solid state. The complex [(β-F_8TPP)Mn^{III}Cl] [**32a(MnCl)**] was obtained by auto-oxidation of [**32a(Mn)**], but attempts to isolate pure [(β-F_8TPFPP)Mn^{III}Cl] [**32b(MnCl)**] were unsuccessful as this latter is readily reduced to the Mn^{II} complex. Nevertheless, the corresponding perchloratomanganese(III) complex [**32b(MnClO$_4$)**] could be obtained in solution by adding iron perchlorate. The complex [(β-F_8TDCPP)Mn^{III}Cl] [**32c(MnCl)**] was prepared by oxidation of [**32c(Mn)**] with iron perchlorate or the ferricinium salt. The manganese(II) complexes display a hypsochromic shift of 13–16 nm when compared with the β-hydrogenated counterparts. The manganese(III) derivatives exhibit a blueshift of only 3–4 nm for the Soret absorption band which is found at 474 nm for [**32a(MnCl)**] and [**32c(MnCl)**]. The redox potentials for the manganese complexes have been determined by cyclic voltammetry. All complexes undergo a reversible Mn^{II}/Mn^{III} process, for example, at $E^1/_2$ = 0.16 V for [(β-F_8TPP)Mn] compared with –0.34 V for [(TPP)Mn] (in CH_2Cl_2, V vs. SCE).[55]

The catalytic behavior of the manganese complexes with PhIO and H_2O_2 as oxidants has been studied by UV/Vis spectroscopy.[55] The robustness of the manganese complexes towards the oxidant in the absence of substrate has been evaluated. With PhIO, 1-methylimidazole (MeIm) was used as co-catalyst and cyclooctene was added prior to measurement to convert high-valent manganese species Mn^{IV} into Mn^{III} derivatives. With or without a co-catalyst, the β-fluorinated Mn^{II} or Mn^{III} complexes are as robust as the hydrogenated counterparts, the sterically protected compounds with the framework TDCPP being particularly stable even under drastic conditions. The activities of the β-fluorinated Mn^{II} or Mn^{III} catalysts in cyclooctene epoxidation were very similar and comparable to those obtained with the β-hydrogenated analogues. The best yields (ca. 73%) were obtained with the TDCPP complexes. Similar activities were found for the Mn^{II} and Mn^{III} catalysts in cyclohexane hydroxylation in the presence of MeIm. The best yield of cyclohexanol (33%) was obtained with [(β-F_8TPFPP)Mn^{II}] [**32b(Mn)**]. As in the epoxidation reaction, the catalytic activity depends on the nature of the aryl group, the phenyl one being the least active. Oxidation with H_2O_2 was also examined in the absence of substrate. Acetonitrile, usually used to dilute hydrogen peroxide, prevents the oxidation of complexes [**32b(Mn)**] and [**32c(Mn)**]. Moreover, this solvent induces the reduction of [**32c(MnCl)**] to the Mn^{II} complex. Finally, methanol was used as co-solvent but under these conditions the most electron-deficient complex [(β-F_8TPFPP)Mn^{II}] [**32b(Mn)**] was found to be unreactive towards H_2O_2. The epoxidation of cyclooctene with ammonium acetate as co-catalyst was studied in mixtures

of dichloromethane/acetonitrile or in methanol. Not surprisingly, the complex [**32b(Mn)**] was inactive in these solvents but the use of acetone as co-solvent and H_2O_2 in an eight-fold excess led to a 32% yield of epoxide versus 44% for the hydrogenated analogue. Under the same conditions, oxidation of cyclohexane led to a low yield of (ol + one), 9 versus 4% with [(TPFPP)Mn^{III}Cl].[55]

Ruthenium Complexes: Che et al.[46a] reported the preparation and characterization of β-octafluorinated ruthenium porphyrin complexes [(β-F_8TPFPP)(CO)Ru^{II}] [**32b{Ru(CO)}**], [(β-F_8TPFPP)(PPh_3)$_2$$Ru^{II}$] [**32b{Ru($PPh_3$)$_2$}**], and [(β-$F_8$TPFPP)($O_2$)$Ru^{VI}$] [**32b{Ru($O_2$)}**]. The dioxoruthenium(VI) porphyrin complex was prepared by oxidation of the carbonyl complex with MCPBA. As outlined above, the crystal structures of the two Ru^{II} complexes showed that the porphyrin rings are essentially planar. Like its β-hydrogenated counterpart, the complex [(β-F_8TPFPP)(O_2)Ru^{VI}] was reactive towards stoichiometric hydrocarbon oxidation at room temperature. Variously *para*-substituted styrenes have been oxidized in good yields and other benchmark substrates have also been used, for example, cyclohexene, norbornene, ethylbenzene, and xanthene. The second-order rate constants (k_2) for the oxidation of alkenes have been determined, inter alia, for the complexes [(β-F_8TPFPP)(O_2)Ru^{VI}] and its β-hydrogenated analogue [(TPFPP)(O_2)Ru^{VI}]. The results showed a significant β-fluorination-induced rate acceleration. For example, styrene was oxidized about 12 times faster with the fluorinated complex than with the hydrogenated one while C–H bond oxidation of xanthene was accelerated by a factor of around 16. A linear correlation between logk_2 and $E_{p,c}$($Ru^{VI/V}$) has been shown, that is, k_2 for the oxidation of a given substrate, for example, styrene or ethylbenzene, increases with the ease of reduction of Ru^{VI} to Ru^{V}. Similarly, a linear correlation between the log of the rate constants and the bond dissociation energies of C–H bonds has been found, providing evidence for hydrogen-atom abstraction in the oxidation of hydrocarbons by dioxoruthenium(VI) complexes.[46a]

Zhang and Che[46b] also examined the catalytic activity of the perfluorinated complex [(β-F_8TPFPP)(CO)Ru^{II}] [**32b{Ru(CO)}**] towards the epoxidation of styrene with 2,6-dichloropyridine *N*-oxide (2,6-Cl_2PyNO), PhIO, or *tert*-butyl hydroperoxide (TBHP) as oxidants. Surprisingly, [(β-F_8TPFPP)(CO)Ru^{II}] was a less efficient catalyst than [(TPFPP)(CO)Ru^{II}], even exhibiting a lower catalytic efficiency than [(TDCPP)(CO)Ru^{II}]. For example, with 2,6-Cl_2PyNO as oxidant, less than 5% conversion was reached after 24 h, with styrene oxide, benzaldehyde, and phenylacetaldehyde formed in a ratio of 32:64:4. Under the same conditions, with [(TPFPP)(CO)Ru^{II}], the conversion was 54% with a ratio of oxidized compounds of 67:20:13. Similar findings were found with PhIO or TBHP as the terminal oxidant. Thus, [(β-F_8TPFPP)(CO)Ru^{II}] was not an effective catalyst for oxidation.[46b]

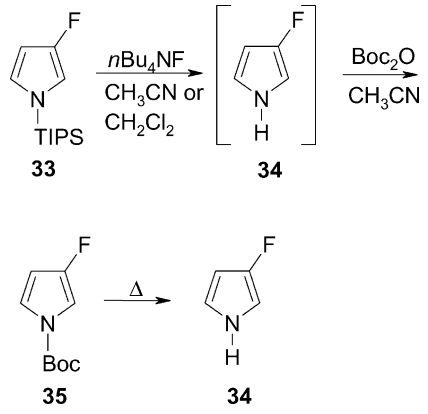
Cobalt Complexes: Despite anticipated impediments intrinsic to the nature of cobalt(II), DiMagno and co-workers have shown that spin-state modulation of a six-coordinate Co^{II} center in β-octafluoroporphyrins was accessible through substantial reduction of the in-plane ligand field by the peripheral electron-withdrawing fluorines with concomitant reduction of nitrogen core basicity.[43] In this study, the compounds [(β-F_8TPP)Co^{II}] [**32a(Co)**] and [(β-F_8TPFPP)Co^{II}] [**32b(Co)**] were prepared by deprotonation of the free-bases with Li(HMDSA) and treatment with anhydrous cobalt chloride in THF at room temperature. The crystal structure of [(β-F_8TPFPP)Co(THF)$_2$] showed that its core size was substantially expanded in comparison to that of [(β-F_8TPFPP)Co(tol)$_2$] (tol = toluene), the Co–N bond being 0.082 Å longer. This change was interpreted in terms of a metal spin-state transition. Solution ^{19}F NMR investigations were performed in the presence of various axial ligands. Large chemical shift variations of the β-fluorine atoms were observed between THF, pyridine or 1-methylimidazole adducts. In the latter adduct, the data were found to be consistent with population of the $d_{x^2-y^2}$ orbital of the metal center and a ^{4}Eg electronic configuration.[43]

In another study, the same group investigated the electron-transfer (ET) properties of the closely related cobalt(II) porphyrins, [(β-F_8TPFPP)Co] [**32b(Co)**], [(β-F_8TPP)Co] [**32a(Co)**], [(TPFPP)Co], and [(TPP)Co]. Cyclic voltammetry linked to digital simulation, in situ UV/Vis and IR spectrometry, kinetic ET studies, bulk electrolysis, ^{19}F NMR spectroscopy, X-ray crystallography, and molecular modeling were used in this study. It was shown, inter alia, that the metal-centered ($Co^{2+/3+}$) heterogeneous ET kinetic rate constants (k_{el}) were reduced in the fluorinated porphyrins by a factor of 10^4 while the self-exchange rate constants (k_{ex}) varied over seven orders of magnitude. The differing ET rates were attributed to widely varying inner-sphere reorganization energies. Spectroscopic, structural, and semi-empirical (PM3) studies indicated that the divergent kinetic behavior of [(β-F_8TPFPP)Co], [(β-F_8TPP)Co], [(TPFPP)Co], and [(TPP)Co] first oxidations arose mainly from the reorganization associated with porphyrin core dilation and contraction.[56]

2.3.7 Partially Fluorinated and Mixed β-Fluoroporphyrins

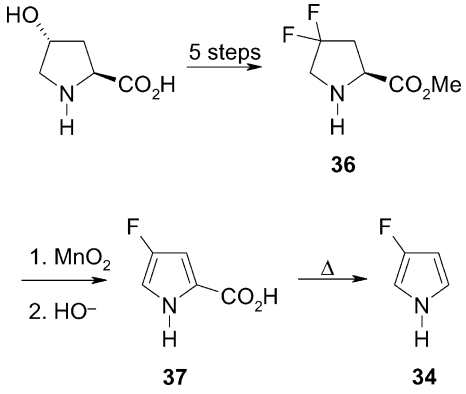
The preparation and study of partially β-brominated and β-chlorinated porphyrins were contemporary with that of the corresponding β-octahaloporphyrins since direct bromination or chlorination most often led to various degrees of halogenation (see above). Whilst direct β-fluorination is not yet possible, the use of β-fluorinated pyrrolic synthons is a solution to the synthesis of partially or fully β-fluorinated porphyrins. The very first examples of such compounds, bearing a limited number of fluorine atoms at the periphery of the macrocycle, were prepared from sophisticated β-fluoropyrroles.[26–28] Apart from these few reports, the rest of the work in this area has been devoted to β-octafluoroporphyrins owing to the recent availability of 3,4-difluoropyrrole. Leroy et al. examined the synthesis of partially β-fluoro-*meso*-tetraphenylporphyrins.[57] Such compounds are of importance since the physicochemical properties of β-octafluoro-*meso*-tetraarylporphyrins are, at least in part, governed by the strong σ-electron-withdrawing character of the peripheral fluorines. Thus, the progressive accumulation

of this atom on the macrocycle could give insights into its role in modulating the physicochemical properties of the macrocycle. Two synthons were retained for the elaboration of the partially β-fluorinated *meso*-tetraphenylporphyrins using Lindsey conditions, namely, 3-fluoro-1*H*-pyrrole (**34**) and 3,4-difluoro-1*H*-pyrrole (**18**). The first pyrrole had not been reported and two routes to this compound were devised. The first one (Scheme 9) started from the known 3-fluoro-1-(triisopropylsilyl)pyrrole (**33**) whose deprotection with tetra-*n*-butylammonium fluoride trihydrate in CH_2Cl_2 afforded the *N*-H pyrrole **34** along with triisopropylsilanol. Isolation of pure pyrrole was unsuccessful due to the presence of residual triisopropylsilanol and (or) solvent. Nevertheless, preparative gas–liquid chromatography (GLC) afforded a few drops of colorless liquid which rapidly turned green-black. The *N*-Boc derivative of **34** appeared more convenient both for easy isolation and subsequent solvent-free deprotection by thermolysis. The in situ *N*-Boc protection of **34** in acetonitrile, without isolation after desilylation, gave only low yields of 3-fluoro-1-(*tert*-butoxycarbonyl)pyrrole (**35**). Flash thermolysis of **35** at 180 °C afforded low amounts of **34** along with an abundant metallic-like deposit.[57]



Scheme 9.

The second route to pyrrole **34** involved the thermal decarboxylation of 4-fluoropyrrole-2-carboxylic acid (**37**) (Scheme 10). This compound was prepared from 4-hydroxy-L-proline through a multistep sequence involving the aromatization of methyl (2*S*)-4,4-difluoro-2-prolinate (**36**) with manganese dioxide. Under the same conditions, methyl (2*S*,4*S*)-4-fluoro-2-prolinate led to methyl pyrrole-2-carboxylate, that is, to the loss of fluorine. Attempted decarboxylation of the acid **37** at 180 °C in the presence of copper powder failed while flash thermolysis at 300 °C was accompanied with extensive decomposition yielding only small amounts of 3-fluoro-1*H*-pyrrole (**34**).[57]



Scheme 10.

β-Fluoroporphyrins (β-F$_n$TPPs, n = 2, 4, 6) from 3,4-Difluoro-1H-pyrrole: Condensation of a mixture of 3,4-difluoropyrrole and pyrrole in an equimolar ratio with benzaldehyde under Lindsey conditions led to a mixture of partially fluorinated porphyrins along with (β-F_8TPP)H_2 and (TPP)H_2 as the major products. Column chromatography of the free-bases then of the zinc complexes afforded four partially fluorinated porphyrins [**38(Zn)**] (n = 2), [*adj*-**39(Zn)**], [*opp*-**39(Zn)**] (n = 4), and [**40(Zn)**] (n = 6) in low yields (Figure 4). These new compounds were characterized by UV/Vis spectroscopy, NMR, and high-resolution mass spectrometry. The UV/Vis absorption spectra of the porphyrins [(β-F$_n$TPP)Zn] are hypsochromically shifted relative to the β-hydrogenated [(TPP)Zn], the observed shifts for the Soret (B) and the two Q bands being linearly correlated to the number (n) of fluorine atoms at the periphery. For example, the Soret band wavelengths follow the simple relationship: λ [nm] = 417.5–1.50n (n = 0, 2, 4, 6, 8) (in CH_2Cl_2) which is consistent with very similar structures for the macrocycles in solution.[57]

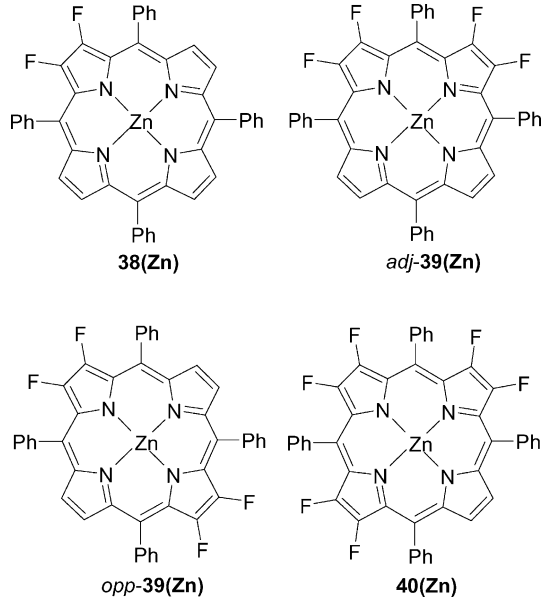
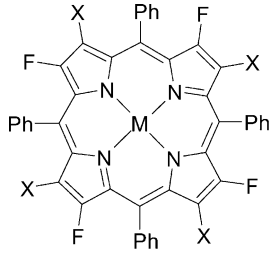


Figure 4. Zinc(II) complexes of partially β-fluorinated *meso*-tetraarylporphyrins prepared from pyrrole and 3,4-difluoropyrrole.

β-Tetrafluoroporphyrins (β-F$_4$TPPs) from 3-Fluoro-1H-pyrrole: Because isolation of substantial quantities of pure 3-fluoropyrrole was problematic, the porphyrin synthesis under Lindsey conditions was conducted directly in the crude dichloromethane solution resulting from the desilylation of pyrrole **33** with *n*-tetrabutylammonium fluoride trihydrate. A mixture of inseparable isomeric β-tetrafluo-

roporphyrins (β-F_4TPP)H_2 (**41**) was obtained after oxidation with DDQ and chromatographic purification (38% yield). Only one regioisomer of the four possible arrangements is represented in Figure 5.[57]



41	X = H, M = 2 H
41(Zn)	X = H, M = Zn
41(Cu)	X = H, M = Cu
41(Ni)	X = H, M = Ni
42	X = Br, M = 2 H
42(Cu)	X = Br, M = Cu
42(Zn)	X = Br, M = Zn

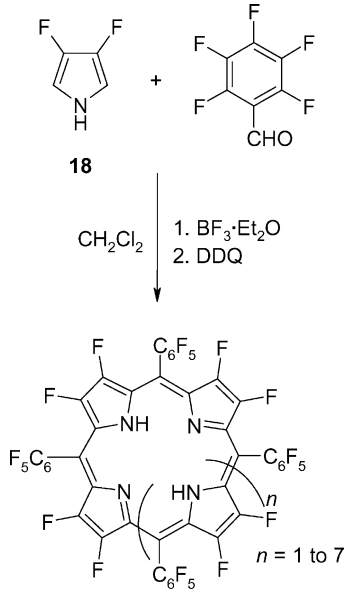
Figure 5. One regioisomer of β-tetrafluoro-*meso*-tetraphenylporphyrin derivatives obtained from 3-fluoropyrrole.

As observed for the symmetrical [*adj*-**39(Zn)**] and [*opp*-**39(Zn)**], the UV/Vis absorption spectra of the porphyrins (β-F_4TPP)H_2 (**41**) and [(β-F_4TPP)Zn] [**41(Zn)**] were blue-shifted relative to the β-hydrogenated counterparts, the shifts (Soret and Q bands) also being half those observed for the β-F_8TPP versus the TPP analogues. Despite the presence of regioisomers, the spectrum of [**41(Zn)**] [λ_{max}(CH_2Cl_2) = 411, 540, 576 nm] did not display a shoulder, nor widening, and was superimposable on that of [**39(Zn)**]. Thus, scattered β-tetrafluorination did not induce major structural differences. β-Tetrafluorination of TPP (H_2 and Zn) resulted in positive shifts of the oxidation and reduction potentials that are the average of the corresponding values for the TPPs and β-F_8TPPs. Remarkably, the NH chemical shift of porphyrins **41**, a singlet at –3.45 ppm, is the average of the values for (TPP)H_2 and (β-F_8TPP)H_2.[57]

The copper(II) β-tetrafluoroporphyrins [(β-F_4TPP)Cu] [**41(Cu)**] were brominated with bromine giving access to the mixed haloporphyrins [(β-Br_4β′-F_4TPP)Cu] [**42(Cu)**]. Demetalation (sulfuric acid) afforded the free-bases (β-Br_4β′-F_4TPP)H_2 which were converted into their Zn^{II} complexes [(β-Br_4β′-F_4TPP)Zn] [**42(Zn)**] (Figure 5). As anticipated, the UV/Vis absorption spectra of the mixed haloporphyrins are redshifted with respect to their β-tetrafluorinated precursors. For the Soret band, the shifts vary from 11 (Zn complex) to 15 nm (free-base).[57]

2.4 Perfluorinated Expanded Porphyrins

A series of *meso*-pentafluorophenyl expanded porphyrins were synthesized by Furuta and co-workers from 3,4-difluoropyrrole (**18**) and pentafluorobenzaldehyde under modified Lindsey conditions (Scheme 11).[58] Relatively high concentrations, around 67 mM in both the reactants in CH_2Cl_2, were used with BF_3·Et_2O as the catalyst. After oxidation with DDQ, chromatographic separation gave porphyrin **32b** (*n* = 1, 6–9%), pentaphyrin (*n* = 2, about 1%), hexaphyrin (*n* = 3, 2–5%), heptaphyrin (*n* = 4, 4–6%), octaphyrin (*n* = 5, 4–7%), nonaphyrin (*n* = 6, about 2%), and decaphyrin (*n* = 7, about 2%). β-Fluorinated hexaphyrin (26π electrons) exhibited a UV/Vis spectrum (Soret-like band at 560 nm) quite similar to that of the β-H analogue, suggesting an aromatic character for the perfluorinated compound. The X-ray crystal structure of its reduced form, [28]hexaphyrin, revealed a noticeable twisted figure-of-eight conformation.[58]

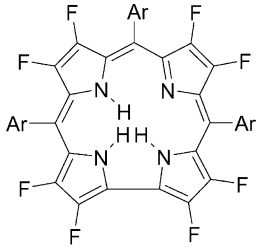


Scheme 11.

2.5 β-Octafluorocorroles

In 2003, the Ghosh and Chang groups reported the one-pot syntheses of β-octafluoro-*meso*-triarylcorroles from 3,4-difluoropyrrole (**18**) and an aromatic aldehyde.[59,60] Although Gross' solvent-free alumina-supported procedure for the preparation of β-hydrogenated corroles worked for the preparation of β-octafluoro-*meso*-tris(*p*-X-phenyl)corroles [**43(X)**] (X = CF_3, H, CH_3, OCH_3; 4 h at 70 °C; yields: 6–8%),[59] 2,3,7,8,12,13,17,18-octafluoro-5,10,15-tris(pentafluorophenyl)corrole (**44**) needed an increased reaction time and temperature (12 h at 100 °C; 5% yield) (Figure 6).[60] The Cu and FeCl derivatives of the ligands [**43(X)**] were prepared and studied by NMR spectroscopy, X-ray photoelectron (XPS), and UV/Vis spectroscopy. The strongly electron-deficient character of the β-octafluorocorrole ligands was evidenced. Cyclic voltammetry revealed that the oxidation half-wave potentials of the Cu and FeCl complexes were positively shifted by 300–400 mV relative to the β-unsubstituted analogues.[59] Similarly, a 490 mV positive shift compared with the β-hydrogenated analogue was determined for the Mn^{III}/Mn^{IV} couple of the manganese(III) derivative of perfluorocorrole **44**. This Mn^{III} corrole was tested as a catalyst in the oxidation of styrene and cyclohexene using PhIO as the oxygen source. A much higher turnover rate was observed when compared with the nonfluorinated analogue, while the perfluorinated catalyst proved to be extremely robust. The reactive intermediate, an oxomanganese(V) complex, was prepared from the reaction of the perfluorinated Mn^{III} corrole with PhIO (half-life ca. 4 h at 25 °C in CH_2Cl_2) and allowed to react with

cyclooctene. Compared with the β-hydrogenated analogue, a 28-fold rate increase in the oxidation of cyclooctene (at 25 °C) was observed.[60]



43(X) Ar = *p*-X-C_6H_4
44 Ar = C_6F_5

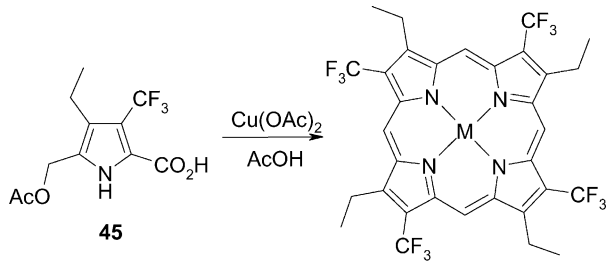
Figure 6. β-Octafluoro-*meso*-triarylcorroles.

3. β-(Perfluoroalkyl)porphyrins

Of the numerous electron-withdrawing groups, the perfluoroalkyl ones display unique properties associated with their strong σ-electron-withdrawing character, exempt from π-electron donation. So, the replacement of β-pyrrolic hydrogens in porphyrins with such groups could bestow peculiar features on the macrocyclic properties. Of the β-perfluoroalkyl substituents, the purported chemically inert trifluoromethyl group has been the most studied.

3.1 Synthesis of β-(Trifluoromethyl)porphyrins

The first preparation of a partially β-trifluoromethylated porphyrin, 2,7,12,17-tetraethyl-3,8,13,18-tetrakis(trifluoromethyl)porphyrin (**46**), was reported by Ogoshi and co-workers.[61a] It involved a copper-mediated condensation/cyclization of the β-(trifluoromethyl)pyrrole **43**. This synthon[61b] was prepared from ethyl trifluoroacetate through a multistep sequence involving a modified Knorr condensation (Scheme 12).[61a]

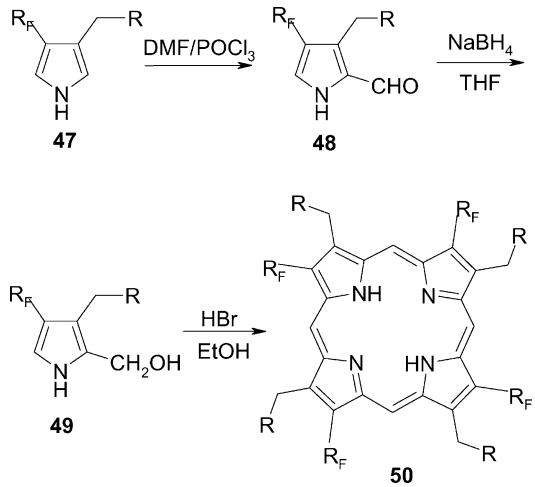


45

46(Cu) M = Cu^{II}
46 M = 2 H

Scheme 12.

Some starting α-unsubstituted β-perfluoroalkylated β′-alkylated *N*-H pyrroles (R_F = CF_3 or C_3F_7) were prepared by using the van Leusen method, that is, by the reaction of *p*-toluenesulfonylmethyl isocyanide (TOSMIC) with a β-perfluoroalkyl α,β-unsaturated ketone in the presence of sodium hydride in Et_2O/DMSO. The Vilsmeier formylation of the intermediate α-free asymmetric pyrrole **47** was regiospecific, revealing marked differences in the electronic effects of β-alkyl and -perfluoroalkyl groups. Reduction of the aldehyde **48** led to the air-sensitive α-(hydroxymethyl)pyrrole **49**. Acidic cyclotetramerization of **49** in the presence of hydrobromic acid led to the corresponding β-(perfluoroalkyl)-porphyrins **50** in 10–30% yields (Scheme 13).[62a,62c]

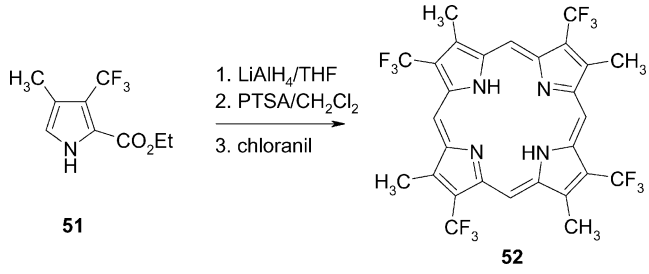


47 **48** **49** **50**

R_F = CF_3, $(CF_2)_2CF_3$; R = CH_3, C_6H_5, OCH_3
R_F = CF_3; R = C_6H_4-*p*-CO_2CH_3, -*p*-CO_2H

Scheme 13.

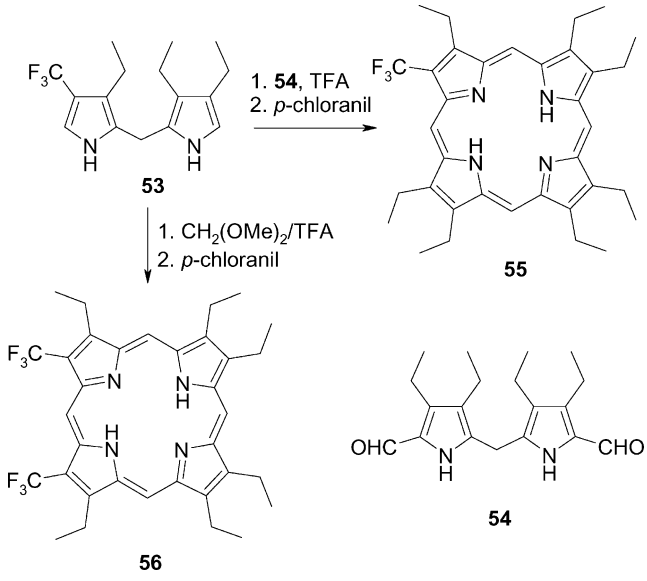
Of the β-trifluoromethylated pyrroles prepared by the Barton–Zard method, the pyrrole **51** was converted selectively into porphyrin **52** (14% yield) by reduction of the ester group with $LiAlH_4$ followed by treatment with PTSA and oxidation with chloranil (Scheme 14).[62b]



51 **52**

Scheme 14.

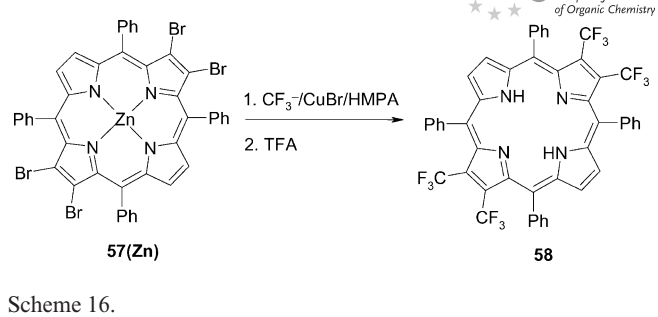
The iron(III) complexes of mono- and bis-trifluoromethylated porphyrins **55** and **56** have also been prepared by Ogoshi and co-workers.[63] The free-bases were obtained by acid-catalyzed coupling of β-(trifluoromethyl)dipyrromethane **53** with diformyldipyrromethane **54** or dimethoxymethane, respectively (Scheme 15), and subsequent oxidation of the porphyrinogen with *p*-chloranil.



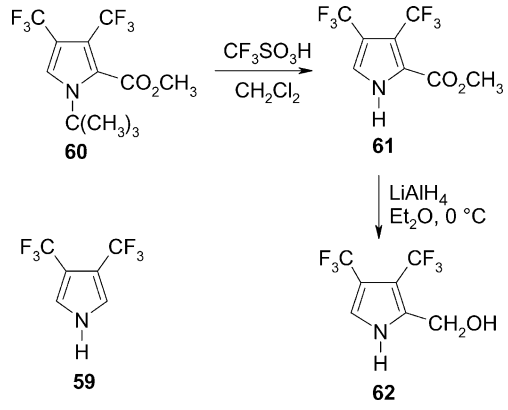
Scheme 15.

Using a different approach, Dolphin and co-workers synthesized partially β-trifluoromethylated *meso*-tetraphenylporphyrins to investigate the steric and electronic effects of the trifluoromethyl groups on the macrocycle.[64] Preparation of the free-base [β-$(CF_3)_4$TPP]H_2 (**58**) involved nucleophilic trifluoromethylation of the macrocycle by reaction of the zinc complex [**57(Zn)**] of the antipodal β-tetrabromo-*meso*-tetraphenylporphyrin (β-Br_4TPP)H_2 with CF_3Cu generated in situ from the metathesis of trifluoromethylcadmium [$(CF_3)_2Cd$ and CF_3CdBr] with CuBr in HMPA (Scheme 16).[64b] Partially trifluoromethylated porphyrins [β-$(CF_3)_2$TPP]H_2 and [β-$(CF_3)_3$TPP]H_2 were also obtained in low yields along with significant amounts of partially brominated and trifluoromethylated TPPs. The yield of **58** was improved by up to about 40% by increasing the reaction temperature. The zinc(II) complex [**58(Zn)**] was obtained from the free-base by a standard procedure[64a] while preparation of the hemin [**58(FeCl)**] required a special procedure (see below).[64c] The electronic structure of the antipodal, partially β-trifluoromethylated TPPs was shown to display intriguing features. For example, NMR experiments showed that the 18π-electron pathway of the free-base **58** is locked in place. Two distinct NH protons not in exchange were seen, confirming that conjugated electron pathways of the porphyrin macrocycle tend to avoid electron-withdrawing substituents on the pyrrolic β positions.

Until the recent work of Liu and Chen (see below),[65] access to β-octakis(trifluoromethyl)porphyrin remained challenging. Although 3,4-bis(trifluoromethyl)-1*H*-pyrrole (**59**) has been available since the first preparations of this synthon in 1982,[66] no successful cyclization of this pyrrole with aldehydes has been reported since. We have also found that the condensation of pyrrole **59** with benzaldehyde under Lindsey conditions or with formaldehyde, in analogy to the synthesis of 2,3,7,8,12,13,17,18-octachloroporphyrin,[24] failed. Undoubtedly, the low electron density at the α positions is responsible for the reluctance of this pyrrole to cyclize with aldehydes owing to the destabilization of reaction intermediates. Some other observations confirmed this deactivation. For example, on *N*-dealkylation with trifluoromethanesulfonic acid in dichloromethane, the ester **60** produced exclusively the *N*-deprotected pyrrole **61** (Scheme 17).[37] No *C*-alkylated isomer was formed in contrast to what was observed in the same dealkylation reaction with the 3,4-difluoro analogue **18**.[30] Furthermore, the strongly deactivated pyrrole **61** did not afford a dipyrromethane in the presence of PTSA/$CH_2(OMe)_2$ in contrast to its 3,4-difluoro analogue **16a** (see above). In our hands, 3,4-bis(trifluoromethyl)-2-(hydroxymethyl)pyrrole (**62**), prepared by reduction of the ester **61**, failed to cyclotetramerize into the corresponding *meso*-unsubstituted porphyrinogen in the presence of PTSA, in contrast with less deactivated β-(trifluoromethyl) 2-(hydroxymethyl)pyrroles.[62]



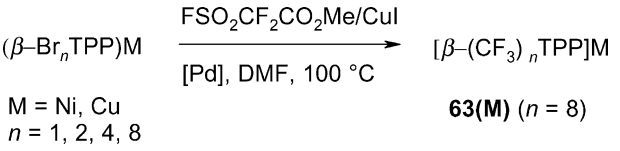
Scheme 16.



Scheme 17.

Owing to the lack of reactivity of such strongly deactivated pyrroles, direct trifluoromethylation of a preformed porphyrin appeared to be the only possible route to a β-octakis(trifluoromethyl)porphyrin. A synthesis of trifluoromethylated porphyrins by a palladium-catalyzed cross-coupling reaction of various β-brominated metalloporphyrins with $FSO_2CF_2CO_2Me$·CuI in the presence of catalytic amounts of $[Pd_2(dba)_3(CHCl_3)]$/$AsPh_3$ (dba = dibenzylideneacetone) has been reported (Scheme 18).[65] Isolated yields were remarkably high, for example, 95% for M = Cu, *n* = 4 and 90% for M = Ni, *n* = 8. Demetalation of the complexes [{β-(CF_3)TPP}Cu] and [{β-$(CF_3)_4$TPP}Cu] with concentrated sulfuric acid afforded the corresponding free-base porphyrins while treatment of [{β-$(CF_3)_8$TPP}Cu] [**63(Cu)**] under similar conditions resulted in the destruction

of the porphyrin macrocycle. The reaction worked also for the introduction of one or two trifluoromethyl groups at the *meso* positions starting from the corresponding brominated porphyrins.



Scheme 18.

3.2 Some Properties of β-Trifluoromethylporphyrins

Solid-State Structures: In addition to its strong σ-electron-withdrawing character, the bulky trifluoromethyl group, with a van der Waals radius of around 2.2 Å, induces steric strain in the porphyrin macrocycle as a result of interactions with the π cloud of the phenyl groups. The X-ray crystal structures of the Zn^{II}[64a] and Cu^{II}[65] complexes of [β-(CF$_3$)$_4$TPP]H$_2$ (**58**) have been established. In particular, that of [{β-(CF$_3$)$_4$TPP}Zn(EtOH)$_3$] revealed a severely saddle-distorted, slightly ruffled macrocycle core. As for the antipodal tetrabromo and tetramethyl analogues, a significant difference in the Zn–N distances between the β-substituted and the non-β-substituted side was observed. The Zn atom was displaced by 0.325 Å from the N_4 mean plane. This especially large displacement was attributed to a combination of steric and electronic effects.[64a] The X-ray crystal structure of the complex [{β-(CF$_3$)$_8$TPP}Ni^{II}] **[63(Ni)]** also showed a severe ring distortion.[65]

Redox Potentials: Cyclic voltammetry measurements on the series [β-(CF$_3$)$_n$TPP]H$_2$ (n = 0, 2, 3, 4) showed that the redox potential gap (the HOMO–LUMO gap) decreases progressively as the number of trifluoromethyl groups increases. For example, the observed gap for **58** was 1.42 versus 2.22 V for (TPP)H$_2$. This contraction in the gap is prominent despite macrocycle distortion and was attributed to the unique electronic structure.[64b] In relation to this HOMO–LUMO narrowing, significant redshifts of the absorption spectra, compared with benchmark porphyrins, were observed. For example, the UV/Vis spectrum of 2,3,12,13-tetrakis(trifluoromethyl)-5,10,15,20-tetraphenylporphyrinato]zinc(II) [{β-(CF$_3$)$_4$TPP}Zn] **[58(Zn)]** [λ_{max}-(CH$_2$Cl$_2$) = 442, 662 nm] was clearly redshifted relative to that of its tetramethyl analogue in the same solvent [λ_{max} = 420, 534 (sh), 551, 587 nm (sh)].[64a] The Fe^{III}/Fe^{II} redox potential of the hemin **[58(FeCl)]** (0.05 V vs. SCE in PhCN) is similar to that of the complex [(β-Cl$_8$TDCPP)FeCl] (0.10 V) and positively shifted from the value of –0.32 V for [(TPP)FeCl]. Nevertheless, this positive shift alone appeared to be insufficient to improve the catalytic ability of the hemin.[64c]

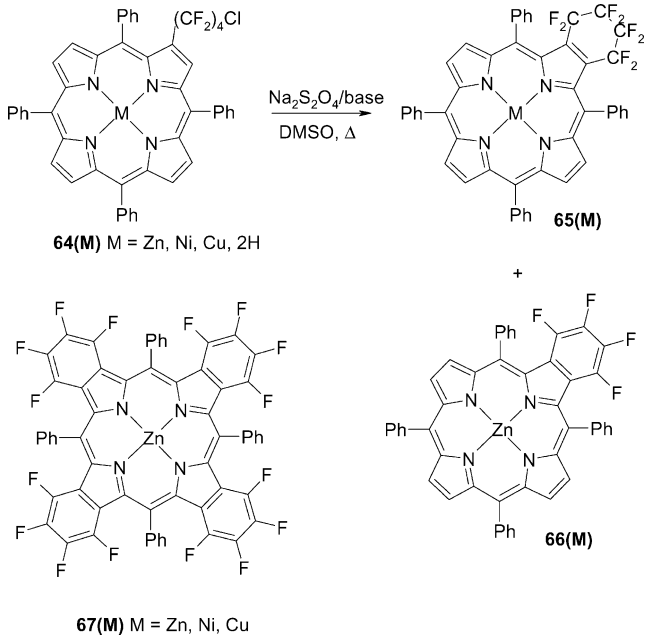
***Catalysis*:** Olefin oxidations catalyzed by Fe^{III} and Mn^{III} complexes of 2,7,12,17-tetraethyl-3,8,13,18-tetrakis(trifluoromethyl)porphyrin (**50**; R_F = CF_3, R = CH_3) by using PhIO as oxidant were investigated in a comparison with the Fe and Mn complexes of octaethylporphyrin (OEP). The relative reactivities in olefin epoxidation were quite similar for a given metal. Moreover, the selectivity of norbornene oxidations with the same oxidant was not seriously affected by the electron-deficiency of the central metal of the trifluoromethylated porphyrin.[67] More recently, an evaluation of the related hemin **[58(FeCl)]** as an oxidation catalyst was made.[64c] Insertion of iron into the macrocycle of the free-base **58** to give the hemin [{β-(CF$_3$)$_4$TPP}FeCl] **[58(FeCl)]** required the formation of the lithium complex, from lithium bis(trimethylsilyl)amide, followed by treatment with ferrous chloride. The potential of hemin **[58(FeCl)]** as an oxidation catalyst was evaluated by using cyclohexane and cyclohexene as substrates and iodosylbenzene as oxidant. A comparison of its performances with that of the complexes [(β-Br$_4$TPP)FeCl] **[57(FeCl)]** and [(β-Cl$_8$TDCPP)FeCl] showed a comparable activity in the oxidation of cyclohexene but the catalysts **[57(FeCl)]** and **[58(FeCl)]** were destroyed during the oxidation of cyclohexane giving low yields of cyclohexanol and low turnovers. Thus, the hemin **[58(FeCl)]**, in spite of its electron-deficient nature, was found to be ineffective as an oxidation catalyst.[64c]

3.3 Other Routes to (Perfluoroalkyl)porphyrins

A general method for the synthesis of *meso*- and β-perfluoroalkylated porphyrins by Pd-catalyzed cross-coupling has also been developed by Liu and Chen.[68] Various metalated β-brominated *meso*-tetraphenylporphyrins [(β-Br$_n$TPP)M] (n = 1, 4, 8; M = Zn^{II}, Cu^{II}, Ni^{II}) (or *meso*-brominated *meso*-diphenylporphyrins in the case of *meso*-perfluoroalkylation), when treated with a perfluoroalkyl iodide (R_FI = IC_4F_8Cl, $IC_6F_{12}Cl$, or IC_6F_{13}) in the presence of excess copper and catalytic [Pd$_2$(dba)$_3$(CHCl$_3$)]/AsPh$_3$ in DMSO at 100 °C, afforded good yields of β-perfluoroalkyl-*meso*-tetraphenylporphyrins. Nevertheless, with n = 4 or 8, only half of the bromine atoms were substituted by perfluoroalkyl groups, leading to inseparable mixtures of isomers. The remaining bromines were reduced during the catalytic cycle to be replaced by hydrogens.[68] The same group showed that treatment of 5,10,15,20-tetraarylporphyrins with perfluoroalkyl iodides in the presence of sodium dithionite (Na$_2$S$_2$O$_4$)/NaHCO$_3$ in DMSO/CH$_2$Cl$_2$ at 30–40 °C (the so-called sulfinatodehalogenation method) gave the corresponding 2-(perfluoroalkyl)porphyrins in moderate yields. The peculiar case of trifluoromethyl iodide was not examined.[69]

Both of the perfluoroalkylation reactions cited above[68,69] have recently found an application in the synthesis of unprecedented tetrafluorobenzoporphyrins, a borderline case of β-(perfluoroalkyl)porphyrins.[70] The method was based on a direct intramolecular cyclization and reductive defluorinative aromatization of β-perfluoroalkylated porphyrins by highly selective C–F bond alkylation under modified sulfinatodehalogenation reaction conditions. Various β-(ω-chloroperfluorobutyl)-*meso*-tetraphenylporphyrins β-(R_FCl)$_n$TPPM [M = Zn^{II}, Ni^{II}, Cu^{II}, or 2H;

n = 1, 2, 4] prepared by palladium-catalyzed cross-coupling reactions or sulfinatodehalogenation (see above) were treated with $Na_2S_2O_4$ in the presence of a base, for example, K_2CO_3 or $NaHCO_3$ in DMSO at 100 °C, affording β-tetrafluorobenzo-*meso*-tetraphenylporphyrins as the major products along with variable amounts of the intermediate β-(octafluorocyclohexenyl)-*meso*-tetraphenylporphyrins, depending upon the reaction conditions. For example, [β-(ω-chloroperfluorobutyl)-*meso*-tetraphenylporphinato]zinc [**64(Zn)**] afforded a mixture of porphyrins [**65(Zn)**] and [**66(Zn)**] (isolated yield 98%) in a ratio of 1:43 when treated with $Na_2S_2O_4/K_2CO_3$ (10 equiv. each) for 30 min (Scheme 19). A proposed mechanism involved the intervention of the radical anion of sulfur dioxide ($SO_2^{\cdot-}$). Variously metalated (M = Zn, Ni, Cu) *opp*-β-di- and β-tetra(tetrafluorobenzo)-*meso*-tetraphenylporphyrins have also been prepared by using the same procedure.[70] The X-ray crystal structures of the zinc(II) complexes of β-mono-, di-, and tetra(tetrafluorobenzo)TPPs have been established. The magnitude of the large distortion of the macrocycle increases with substitution of tetrafluorobenzo groups on the pyrrole ring and culminated with the complex [**67(Zn)**]. Compared with other *meso*-tetraphenylporphyrins, the "π-extended" tetrafluorobenzoporphyrins, exhibited large red-shifts of the absorption bands (Soret and Q bands), attributed mainly to the extended π-conjugation. So, the spectrum of [**67(Zn)**] was found to be bathochromically shifted from around 60 nm with respect to that of [β-tetrabenzo-*meso*-tetraphenylporphyrinato]zinc. This was ascribed to the increased bulkiness of the tetrafluorobenzo group compared with the benzo one. The electron-withdrawing character of the tetrafluorobenzo group was expected to exert a significant effect on the electrochemical properties by stabilizing both the HOMOs and the LUMOs compared with the unsubstituted derivatives, that is, the tetrafluorobenzoporphyrins would be harder to oxidize and easier to reduce. Cyclic voltammetry measurements made on the above Zn^{II} complexes have shown that this is not the case. To the contrary, the data indicated that the tetrafluorobenzoporphyrins were more readily reduced and oxidized with increasing substitution. Furthermore, $E^1/_2$ox(I) – $E^1/_2$red(I) decreased with increasing numbers of tetrafluorobenzo groups, indicating decreasing HOMO–LUMO gaps.[70]



Scheme 19.

4. Conclusion

The advances realized in the chemistry of β-fluoroporphyrins, and more particularly of octafluorinated ones, are recent. They have been rendered possible by the recent availability of, inter alia, 3,4-difluoro-1*H*-pyrrole. The introduction of fluorine atoms or (and) perfluoroalkyl groups into the pyrrolic β positions has led to a variety of novel electron-deficient porphyrins. The synthetic methods used for their preparation involved fluorinated synthons in the case of (indirect) β-fluorination while β-perfluoroalkylation was achieved either through perfluorinated units or by the introduction of perfluoroalkyl groups into a preformed porphyrinic macrocycle. The physicochemical and catalytic properties of various β-octafluoro-*meso*-tetraarylporphyrins have been detailed thus complementing previous studies on haloporphyrins, restricted up to now to their chlorinated and brominated congeners. Since the chemistry of (poly)-fluorinated and (poly)perfluoroalkylated porphyrins is essentially recent, numerous other applications of these ligands and their fluorinated precursors are foreseeable.

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