A new fluorous-tagged porphyrinoid

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A NEW FLUOROUS-TAGGED PORPHYRINOID

BY

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Abstract

The field of corrole chemistry has flourished over the past decade. Simple and high-yielding procedures have made the corrole ligand readily available, and several procedures on how to functionalize and otherwise modify corroles and their metal complexes have been reported.

During an attempt to synthesize corrole from a fluorous tagged aromatic aldehyde a new porphyrinoid has been isolated from the pyrrole-aldehyde condensation, proving that pyrroles and aromatic aldehydes are indeed capable of self-assembling into a variety of macrocycles. This new porphyrinoid is believed to be an isosmaragdyrin, which would be the first report of a smaragdyrin synthesized from a one-pot procedure.

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List of abbreviations and symbols

α – alpha

β – beta

Ar – Aryl

DDQ – 2,3-dichloro-5,6-dicyano-p-benzoquinone

MeOH – Methanol

NaOAc- Sodium acetate

CH_2Cl_2 – Dichloromethane

$CHCl_3$ – Chloroform

AcOH – Acetic acid

HCl – Hydrochloric acid

NMR – Nuclear magnetic resonance

DFT – Density functional theory

TLC – Thin layer chromatography

TFA – Trifluoroacetic acid

DMF – Dimethylformamide

Corroles and related macrocycles

Porphyrins (**figure 1**) are tetrapyrrolic macrocycles occurring naturally in a number of proteins and enzymes, such as hemoglobin, myoglobin, chlorophylls and cytochromes. The porphyrin ring consists of four pyrrole units linked by four methine bridges. The porphyrin macrocycle has 22 π-electrons, 18 of which lie in a delocalized pathway. Upon removal of the core protons, the porphyrin macrocycle can bind a variety of metal ions, acting as a dianionic ligand. The periphery of the macrocycle is easily functionalized as both the *meso-* and *β*-positions may undergo electrophilic substitutions.
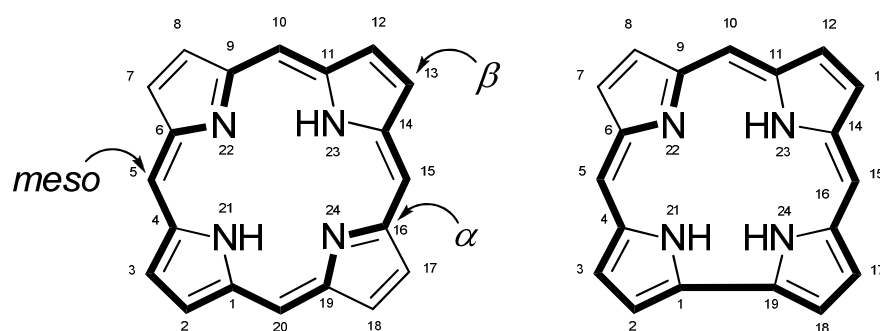
Figure 1. Porphyrin (left) and corrole (right) macrocycles showing atom numbering, nomenclature and highlighting the 18 π-aromatic core.

Corroles are tetrapyrrolic macrocycles, just like the porphyrins, and the two macrocycles are in many ways similar. However, unlike the porphyrin, the corrole has not been found in nature, but a reduced analogue called corrin is present in vitamin B_{12} (**figure 2**).
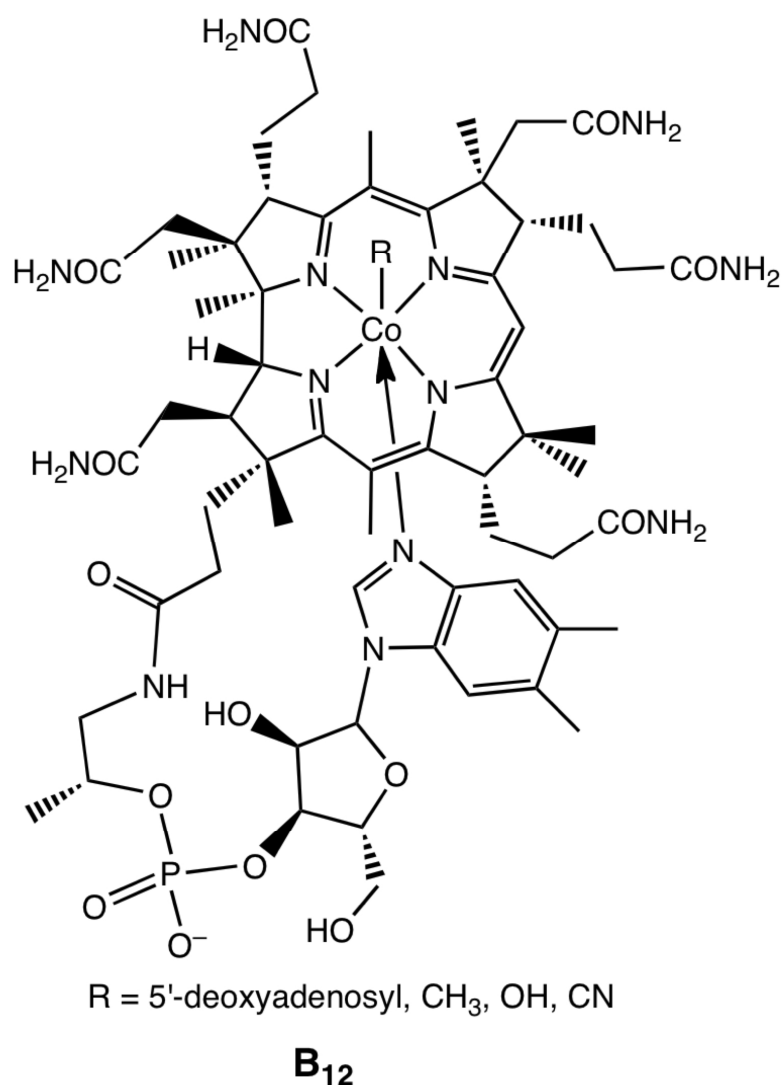
Figure 2. Corrin, a reduced analogue of corrole is present in Vitamin B_{12}.

Corroles distinguish themselves from porphyrins by having a direct bond between two of the pyrrole units. This direct pyrrole-pyrrole link contracts the core and rearranges the electronic structure with the consequence that the corrole has three protons in its core, all of which are easily deprotonated. This means that the corrole is formally a trianionic ligand, unlike the porphyrin which is dianionic. Just as porphyrins the corrole can bind metal ions in its core, but due to its trianionic nature it is capable of binding metals in unusually high oxidation states (e.g. Ag^{III}, Fe^{IV} and Cr^{V}).[1-4]

Both porphyrins and corroles are products of condensations between pyrroles and aldehydes followed by oxidation to yield the aromatic macrocycles. A number of other macrocycles are available from the pyrrole-aldehyde condensation, simply by altering reaction conditions, including triphyrins, N-confused porphyrins, sapphyrins and expanded porphyrins (**figure 3**). In general corroles and porphyrins are prepared from aromatic aldehydes as their synthesis is easy, and the arylated compounds are more stable than their unsubstituted counterparts.
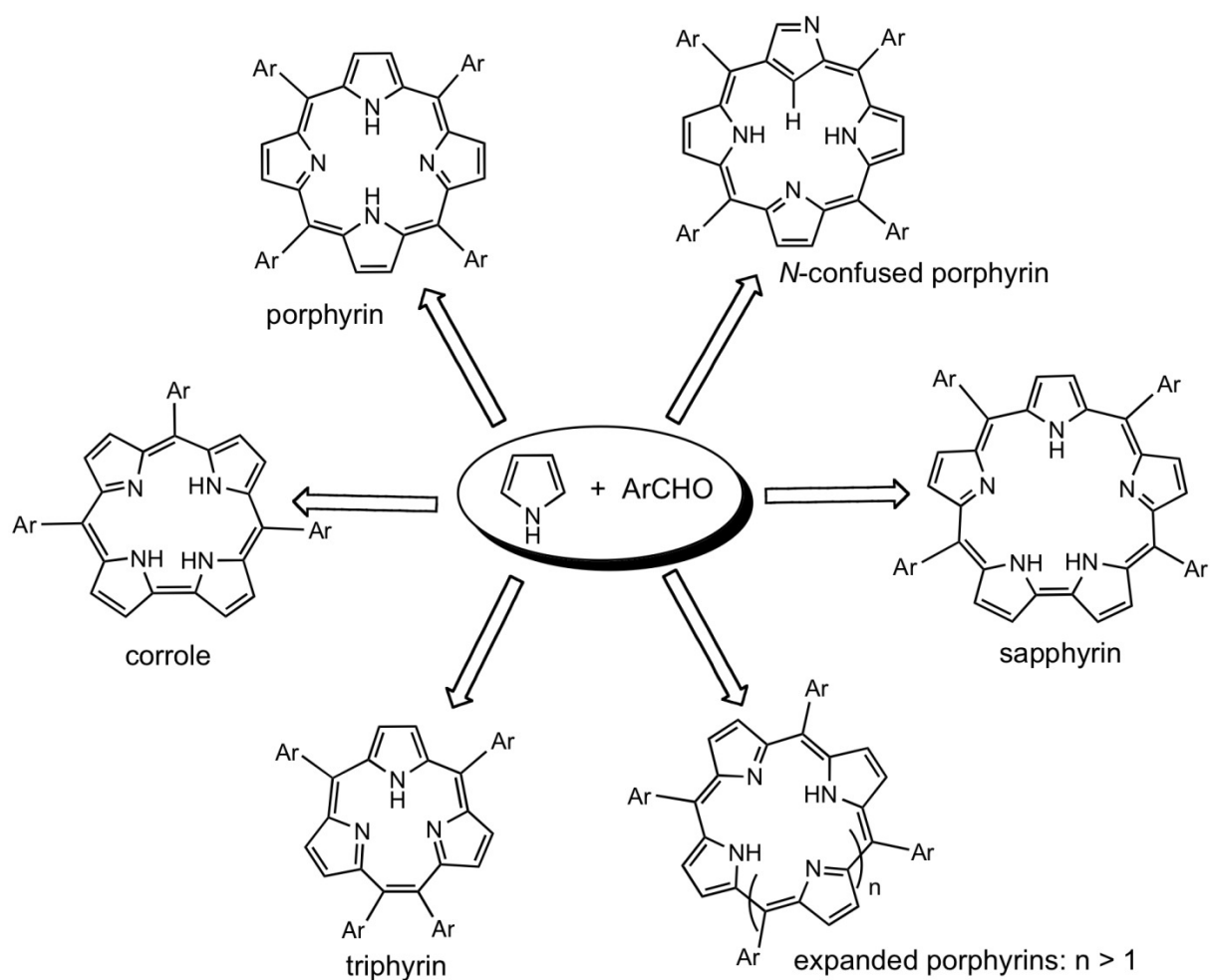

Figure 3. The condensation of pyrroles and aldehydes is a versatile reaction that yields a number of macrocycles depending on the reaction conditions employed.

Corroles in general possess lower symmetry than porphyrins. Planar porphyrins with four equal *meso*-substituents belong to the highly symmetric D_{4h} point group, whereas planar corroles with three equal *meso*-substituents belong to the C_{2v} point group. Both corroles and porphyrins may however adopt nonplanar conformations resulting in lower symmetries, even chiral point groups as is the case for copper corroles.[5-7]

The nomenclature of the corroles *meso*-substitution pattern is similar to that of porphyrins. Corroles with three equal *meso*-substituents are called A_3-corroles. Corroles with equal substituents on the 5 and 15-position and a different substituent on the 10-position are called *trans*-A_2B-corroles, they are however usually just called A_2B-corroles as *cis*-A_2B-corroles are much less common. Corroles with three different *meso*-substituents are called ABC-corroles.

Corroles have been known since 1965 when Johnson and Kay published the first synthesis of a corrole.[8,9] Their method did however require multiple steps of synthesis to acquire the necessary starting materials and as a result the field attracted little interest for over 30 years. Short and high-yielding procedures have only been available since 1999 when the two groups of Paolesse[10] and Gross[11] reported two different procedures leading to 5,10,15-triarylcorroles. Since then, the field of corrole synthesis has been improved, most notably by the Gryko *et al,*[12] but also by the easy and high-yielding procedure for the preparation of dipyrromethanes reported by the group of Dehaen.[13]

Corroles and their metal complexes have been shown to have a wide range of applications.[14] They have been shown to have high catalytic activity,[15] they have been studied as dyes for dye-sensitized solar cells[16] and they have been shown to produce singlet oxygen,[17] making them possible drugs for photodynamic therapy.

Porphyrin synthesis

The first one-pot procedure for the synthesis of porphyrins was published as early as 1935 by Rothemund where pyrrole and aldehydes were condensed in sealed vessels at high temperatures.[18] Adler and Longo later modified this procedure to synthesize tetraphenylporphyrin by refluxing equimolar amounts of pyrrole and benzaldehyde in propionic acid.[19]

The group of Lindsey developed a method utilizing milder conditions allowing synthesis from a wide variety of aldehydes and pyrrole in unprecedented yields. First equimolar amounts of aldehyde and pyrrole were condensed in dichloromethane under inert atmosphere, using either boron trifluoride-etherate ($BF_3 \cdot Et_2O$) or TFA as catalyst. After the porphyrinogen (i.e. porphyrin precursor) was formed, DDQ or *p*-chloranil was added to the reaction mixture to form the porphyrin (**scheme 1**).[20]
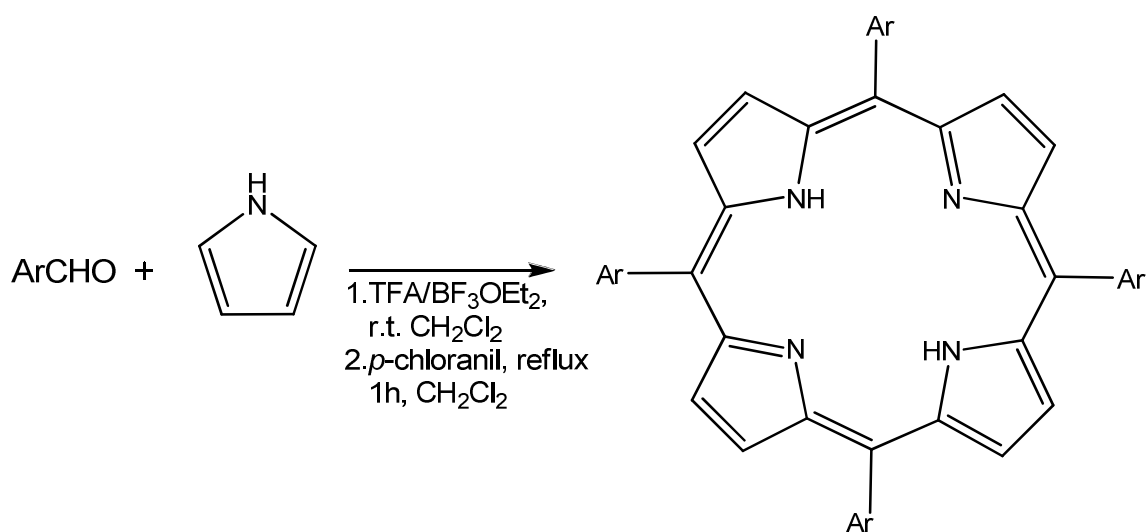
Scheme 1. Lindsey method for porphyrin synthesis.

Ionic liquids have been investigated as reaction media for porphyrin formation in pursuit of green synthesis, as ionic liquids may act as both solvent and catalyst, and may potentially be reusable. The group of Ishikawa screened a series of ionic liquids to investigate the effect of cation and anion structures on the formation of tetraphenylporphyrin, as well as water content and viscosity.[21]

Of the liquids studied [C$_4$mim][TFSI] (**figure 4**) was found to be the best, yielding 41% tetraphenylporphyrin, comparable to the Lindsey method. The ionic liquids were used as solvents in otherwise typical Lindsey reactions, but their reusability became an issue when reaction byproducts proved impossible to remove. To overcome this problem Ishikawa devised a biphasic reaction medium where dichloromethane is placed on top of [C$_4$-SAbim][CF$_3$SO$_3$] (**figure 4**).
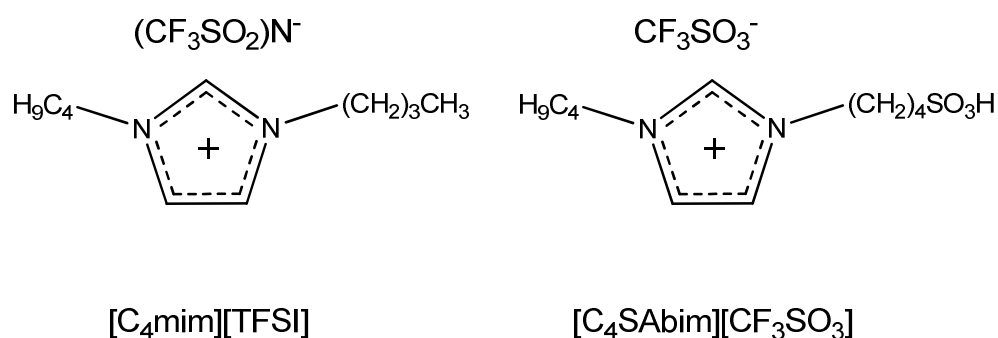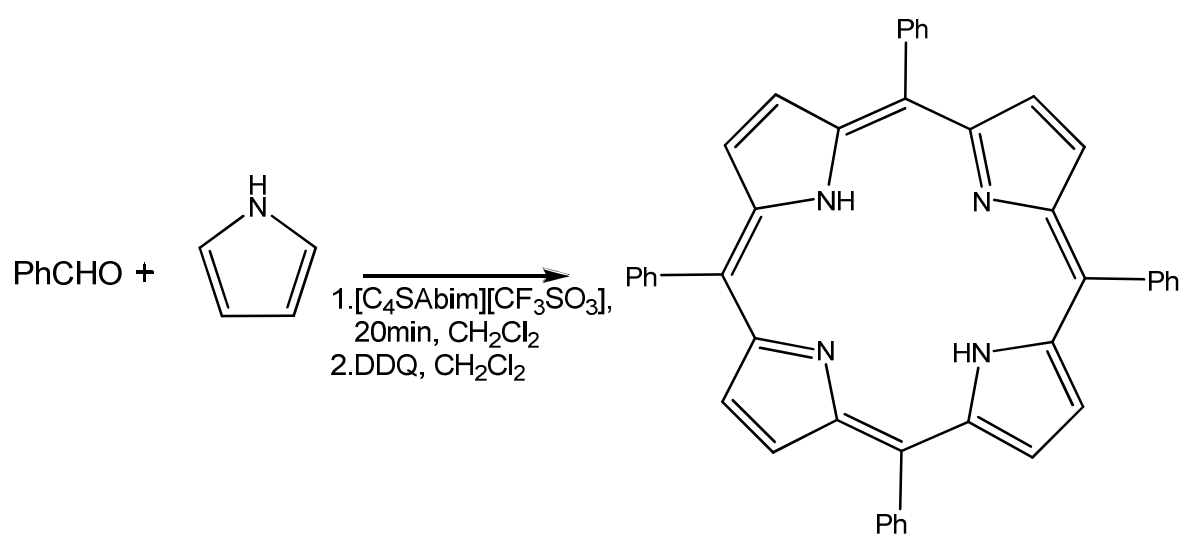

**Figure 4.** Ionic liquids used for porphyrin synthesis.

Pyrrole (14,5 mM) and benzaldehyde (14,5 mM) were added to the dichloromethane phase and allowed to react for 20 minutes with the ionic liquid acting as the reaction catalyst at the interface between the dichloromethane and ionic liquid phases. The dichloromethane phase was then separated from the ionic liquid and DDQ was added to oxidize the porphyrinogen to porphyrin (**scheme 2**).

Scheme 2. Biphasic method for porphyrin synthesis utilizing the ionic liquid [C$_4$-SAbim][CF$_3$SO$_3$].

To minimize the use of dichloromethane the biphasic system was employed at 10-fold higher reactant concentrations, and indeed a yield of 27% was achieved. Furthermore Ishikawa *et al* illustrated that their biphasic reaction medium could be used to synthesize tetraphenylporphyrin in at least 10 consecutive runs at high reactant concentrations with yields ranging from 27-31%.

The group of Chandramouli continued the quest for green synthesis and reported the use of neat 1-butyl-3-methylimidazolium tetrafluoroborate ([bmim][BF$_4$]) to synthesize porphyrins from pyrrole and several substituted aromatic and heteroaromatic aldehydes (**scheme 3**).[22] Yields were in the range of 17-33%. The ionic liquid acted as both solvent and catalyst, while oxygen from the air was the oxidant. Chandramouli did not however report any attempts to reuse the ionic liquid in subsequent runs.
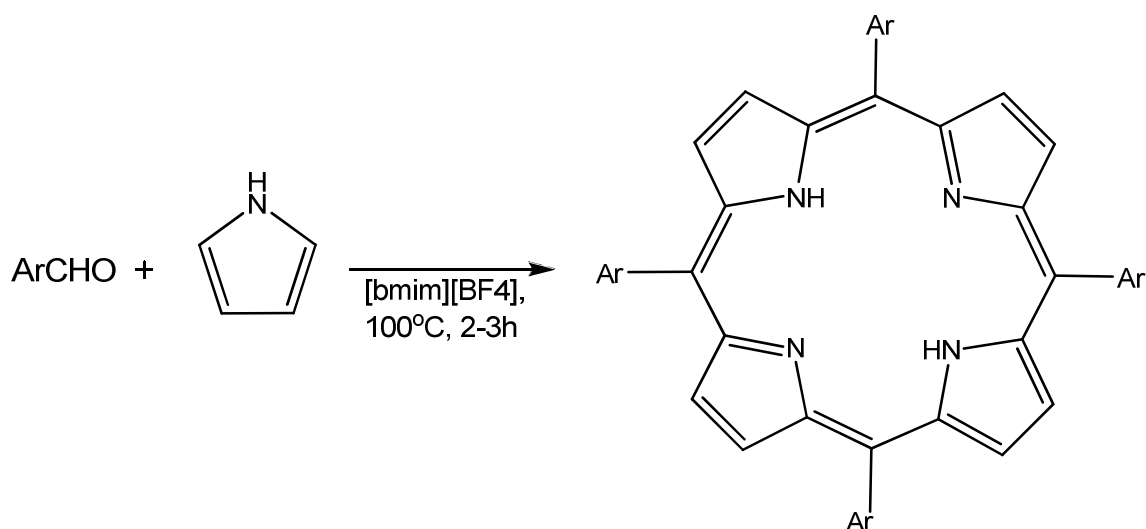
Scheme 3. Green synthesis of porphyrins utilizing only [bmim][BF$_4$], pyrrole and the appropriate aldehydes.

The ionic liquid 1-hexyl-3-methylimidazolium bromide ([hmim][Br]) has been used to metalate porphyrins with iron, manganese and zinc in excellent yields. The appropriate porphyrins and metal salts were stirred in [hmim][Br] for one hour (**scheme 4**). Afterwards the ionic liquid was washed with diethyl ether to retain its reactivity for subsequent runs.[23]
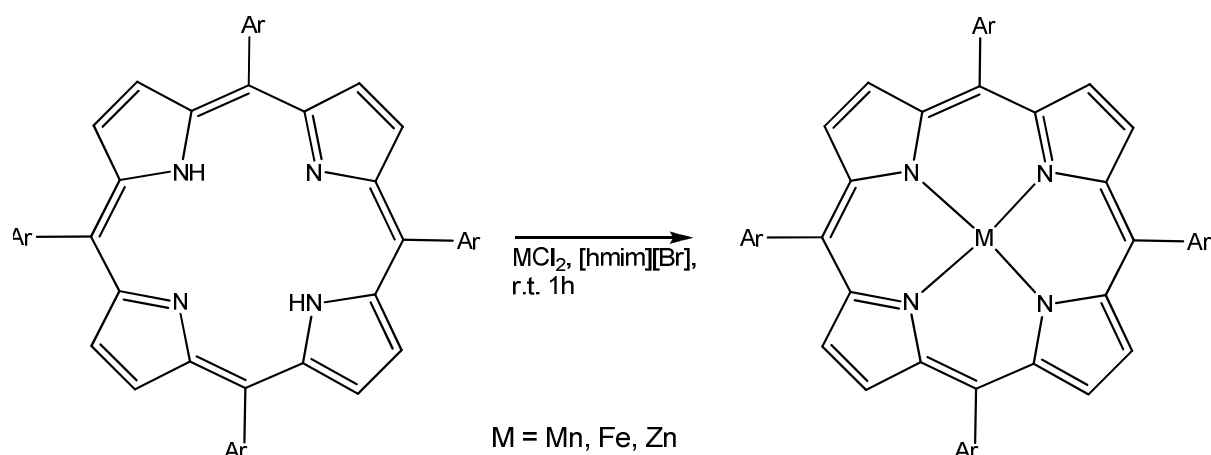
**Scheme 4.** Metalation of porphyrins using the ionic liquid [hmim][Br].

Several one-pot procedures have been developed for the direct synthesis of metalloporphyrins. Pyrrole and aldehydes are condensed in the presence of metal salts yielding metalloporphyrins in higher yields relative to free-base synthesis. Manda *et al* added metal acetates to the propionic acid used in the Adler-Longo method. Cu and Zn porphyrins are synthesized in higher yields while Pb and Mn porphyrins in lower yields relative to free-base synthesis.[24]

The group of Abhilash developed a method where pyrrole and aromatic aldehydes were stirred in DMF followed by addidition of metal salts (**scheme 5**).[25] With this method they were able to produce several different substituted porphyrins with a variety of metals at their core in yields as high as 44%.
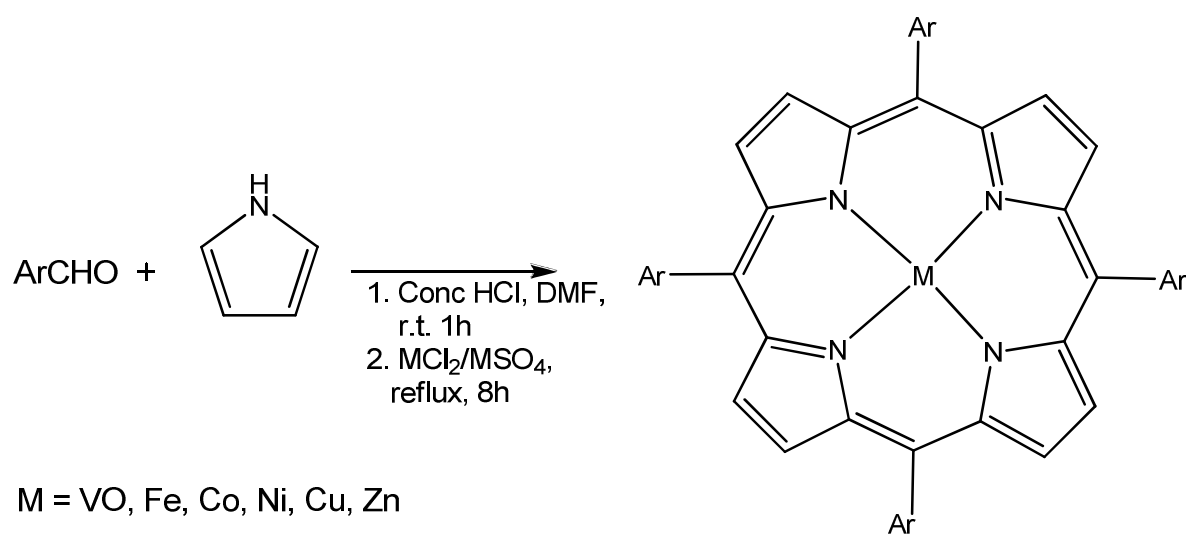
**Scheme 5.** One-pot method for synthesis of metalloporphyrins.

The group of Mirafzal has synthesized Mn-porphyrins in truly impressive yields.[26] By refluxing pyrrole, aromatic aldehydes and $MnCl_2$ in 2,4,6-trichlorophenol they managed to obtain Mn-porphyrins in yields as high as 71% (**scheme 6**).
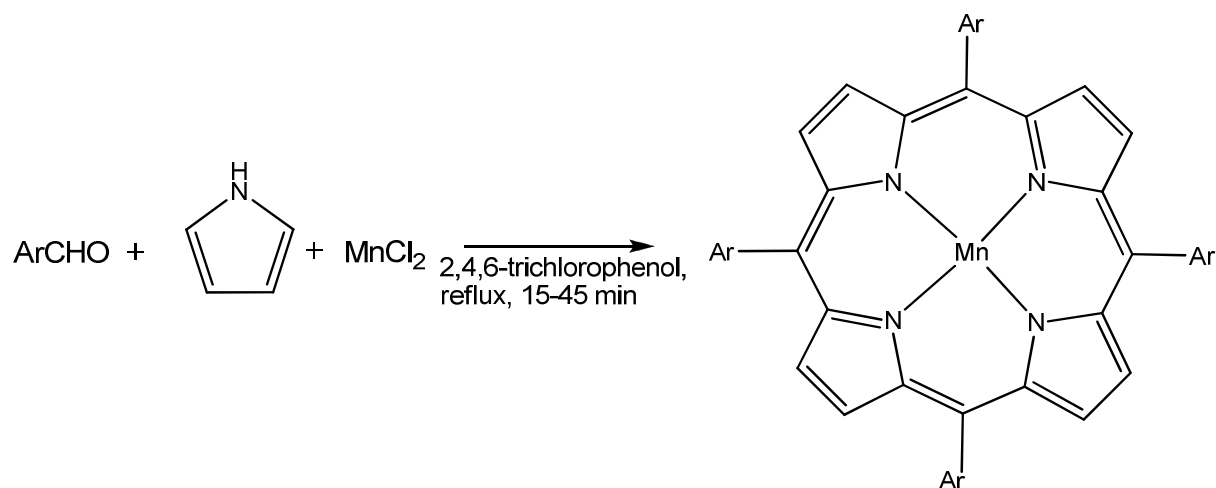
**Scheme 6.** One-pot synthesis of manganese porphyrins

Corrole synthesis

The first successful synthesis of corroles were published by Johnson and Kay in 1965.[8,9] The free-base corroles were obtained by light-irradiation of methanolic suspensions of 1,19-dideoxybiladienes-a,c containing a slight excess of either sodium acetate or ammonium hydroxide (**scheme 7**). The cyclization proceeded in yields ranging from 20-60%.
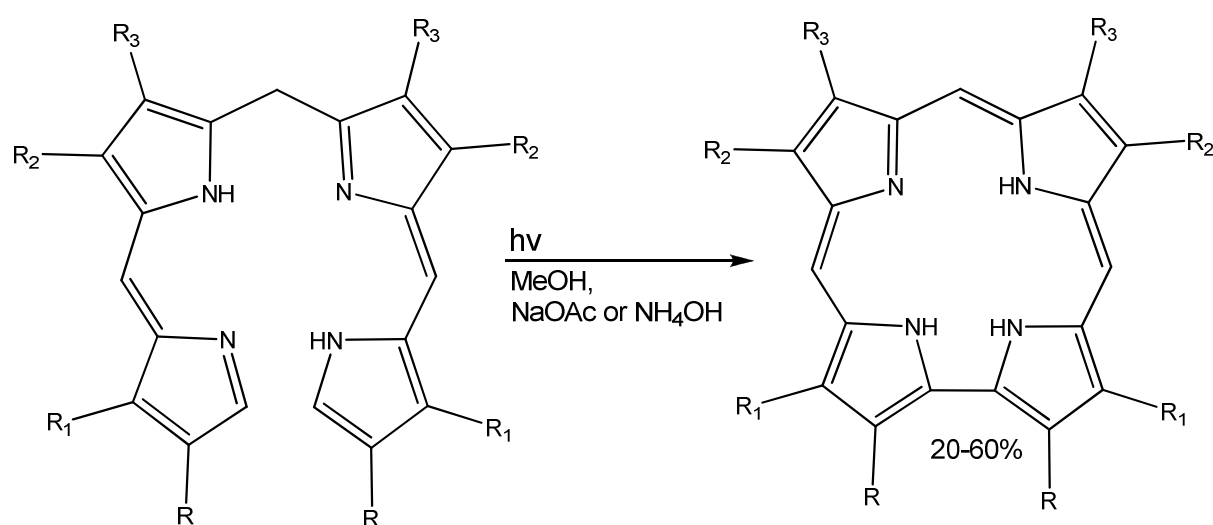
Scheme 7. Cycliation of 1,19-dideoxybiladiene-a,c to yield corrole

The 1,19-dideoxybiladienes-a,c were prepared either by condensation of dipyrromethane-5,5'-dicarboxylic acids with 2 equivalents of 3,4-dialkyl-2-formylpyrrole, or by condensation of 5,5'-diformyldipyrromethanes with 2 equivalents of 3,4-dialkylpyrrole-2-carboxylic acid (**scheme 8**).
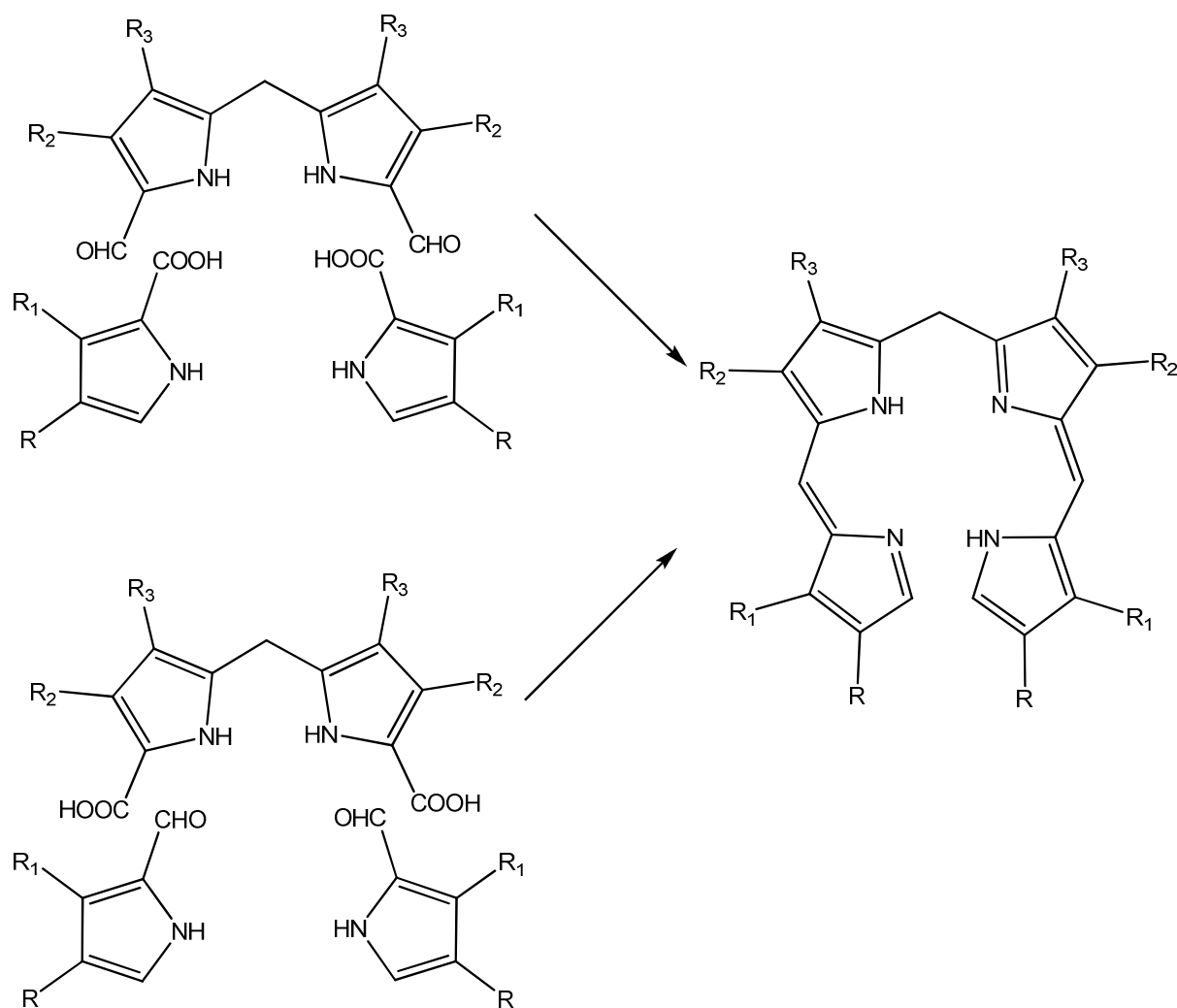
Scheme 8. The two synthetic routes to 1,19-dideoxybiladiene-a,c

Several advances to the corrole field were made. Vogel and co-workers demonstrated the corroles ability to stabilize metals in high oxidation states (e.g. Fe^{IV}, Cu^{III}, Ni^{III}, Co^{IV} and Co^{V}).[1,2,27,28] The group of Paolesse synthesized the first *meso*-substituted corroles (i.e. cobalt complexes of mono, di and triphenylcorroles),[29,30] and synthesized the first corrole from a monopyrrolic precursor,[29] but the synthesis only proceeded in the presence of cobalt ions.

The need to synthesize pyrrole precursors, however, made the entire process of corrole synthesis tedious and overall poor yielding, and as a result the corrole field lay dormant for over 30 years until 1999 when the first simple one-pot procedures for the synthesis of corroles became available as the two groups of Gross[11,31] and

Paolesse[10,32] almost simultaneously reported two different routes for the preparation of 5,10,15-triarylcorroles.

Gross and co-workers reported the synthesis of 5,10,15-tris(pentafluorophenyl)corrole by condensation of equimolar amounts of pyrrole and pentafluorobenzaldehyde on basic or neutral alumina followed by oxidation with DDQ in CH_2Cl_2 (**scheme 9**). 5,10,15-tris(2,6-difluorophenyl)corrole could be synthesized the same way and by altering the pyrrole/aldehyde ratio to 2:1, so could 5,10,15-tris(2,6-dichlorophenyl)corrole.[11,31]
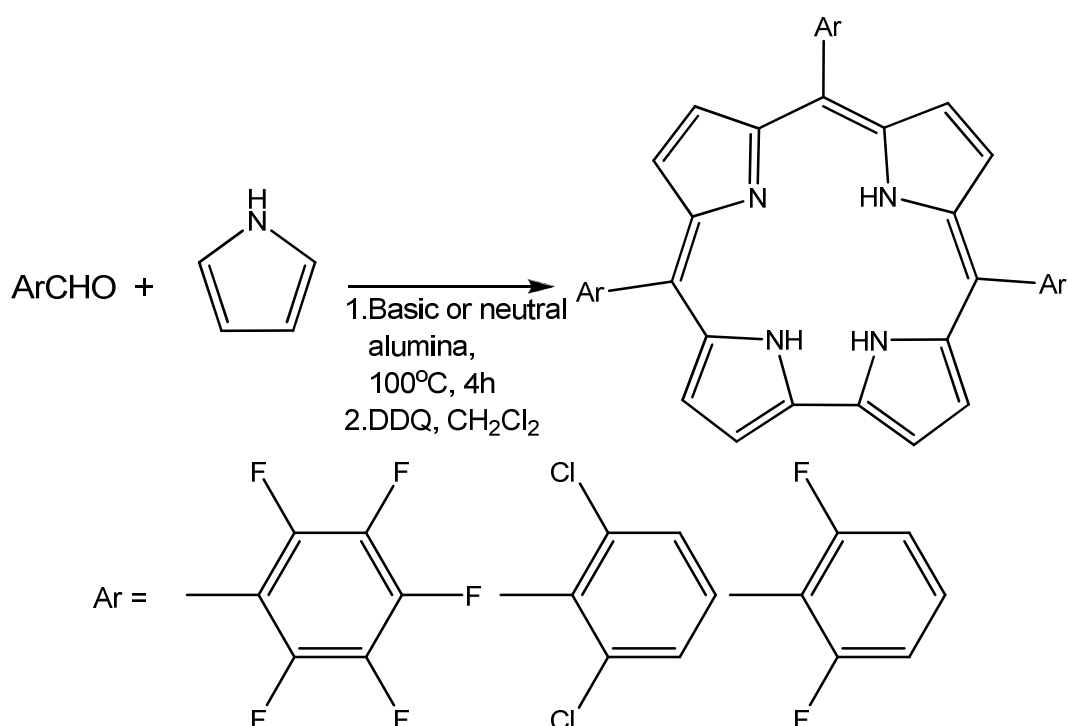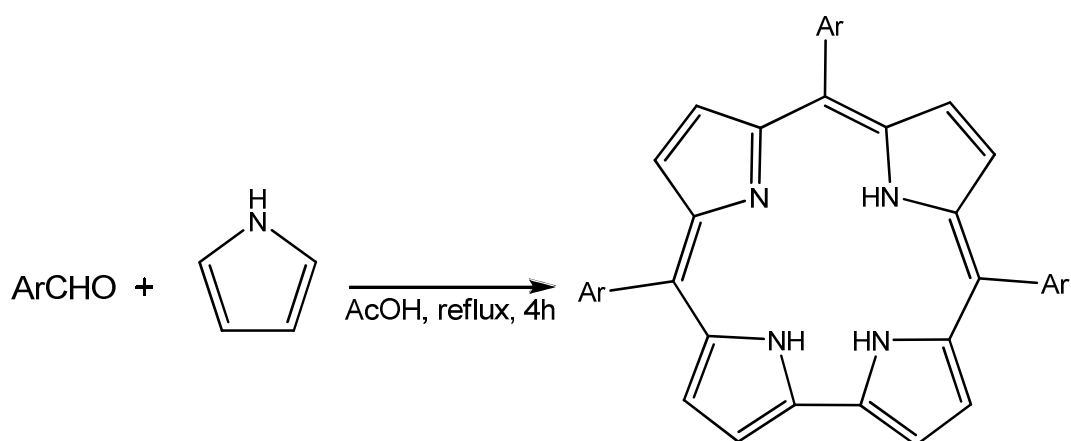

Scheme 9. One-pot method developed by Gross *et al.*

The Gross method was believed to be applicable only to benzaldehydes with electron-withdrawing substituents, but Ghosh and co-workers showed that it was indeed applicable to electron-rich benzaldehydes and they further illustrated that the method could be used to synthesize a series of *β*-octafluorinated *meso*-triarylcorroles, starting from 3,4-difluoropyrrole and several *para*-substituted benzaldehydes (**scheme 10**).[33,34]
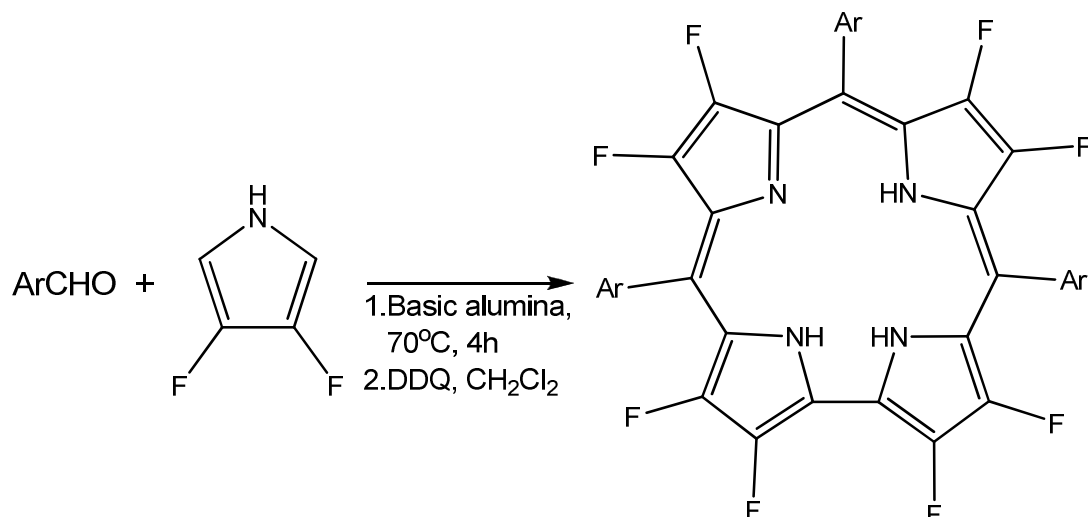
Scheme 10. Gross method expanded by Ghosh *et al* to include electron-rich benzaldehydes and 3,4-difluoropyrrole.

Paolesse and co-workers reported a modified Rothemund procedure where a 3:1 pyrrole/aldehyde molar mixture was refluxed in acetic acid. The corrole was isolated after crystallization of the porphyrin side-product. A year after publishing the original paper Paolesse and co-workers showed that their method was applicable to a series of substituted and heteroaromatic aldehydes (**scheme 11**), but not sterically hindered 2,6-disubstituted benzaldehydes.[10,32]

**Scheme 11.** One-pot method developed by Paolesse *et al.*

A major development in the field of corrole synthesis came in 2006 when Gryko *et al* published a two-pot procedure (formation of bilane, the corrole precursor, and subsequent oxidation) which led to corroles in unprecedented yields.[12] Gryko was inspired by the work done by Kral and co-workers on the synthesis of

dipyrromethane.[35] Kral took advantage of the solubility difference between the starting materials (aldehyde and pyrrole) and the product in water to push the reaction towards dipyrromethane without further condensation. Gryko envisioned that the use of water and a co-solvent could be used in a similar manner to push the condensation reaction towards bilane, and indeed the strategy worked. Optimal conditions were found to be 1:1 water/methanol as solvent, 2:1 pyrrole/aldehyde molar ratio and 0,25 mM 36% hydrochloric acid as the catalyst (**scheme 12**). Oxidation was optimal with *p*-chloranil in acetonitrile, but chloroform was chosen as solvent because it made purification easier and the loss of yield was minimal.
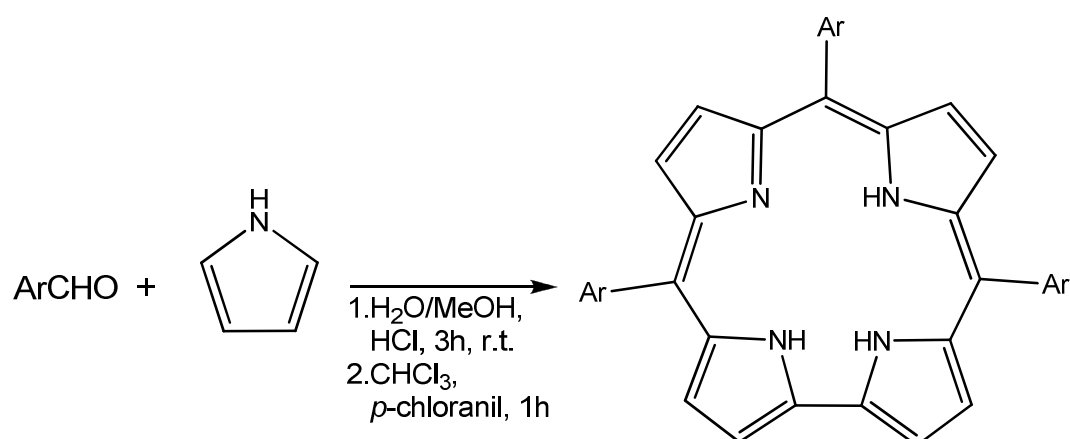
Scheme 12. A two step and highly efficient method for corrole synthesis developed by Gryko and co-workers.

Gryko and co-workers also reported an efficient method for the synthesis of A_2B-corroles in the same paper. 5-aryldipyrromethanes were synthesized in water using hydrochloric acid as a catalyst. The dipyrromethanes were then condensed with aromatic aldehydes followed by oxidation similar to how A_3-corroles are prepared (**scheme 13**). Even though this procedure involves an extra step, the overall yield of the A_2B-method exceeds that of the A_3-method, and can in some cases be over 50%.
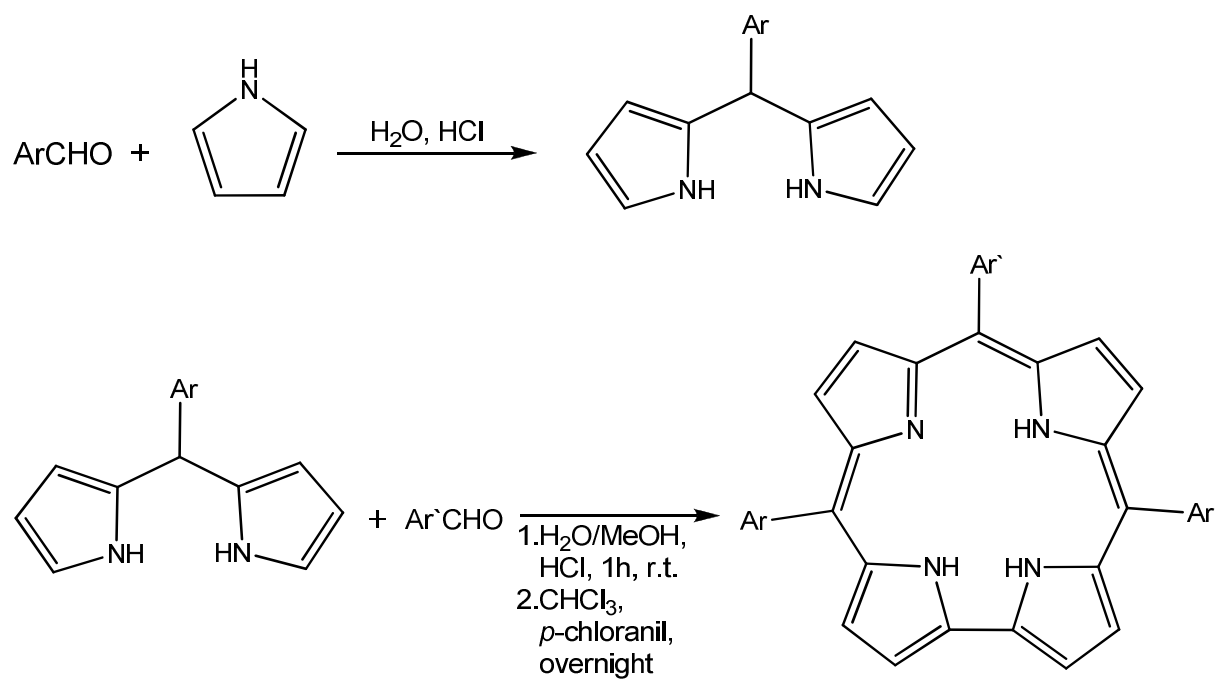
Scheme 13. Gryko`s method for the preparation of A$_2$B-corroles.

Copper corroles

In general, corroles and their metal-complexes are planar regardless of substituents at their periphery (i.e. the pyrrolic *β*-positions). A good example of this is the iridium corroles reported by Gray *et al*,[36] where crystal structures of iridium(III) bis-trimethylamine 5,10,15-tris(pentafluorophenyl)corrole and its octabrominated derivative show almost perfectly planar complexes (**figure 5**). These observations are in contrast to porphyrins, where nonplanar distortions due to steric effects are common. Some domed corrole complexes are known (e.g. MoO[37], RhPPh$_3$[38] and diboron-complexes[39]), but the truly unique metallocorrole complex is that of copper.
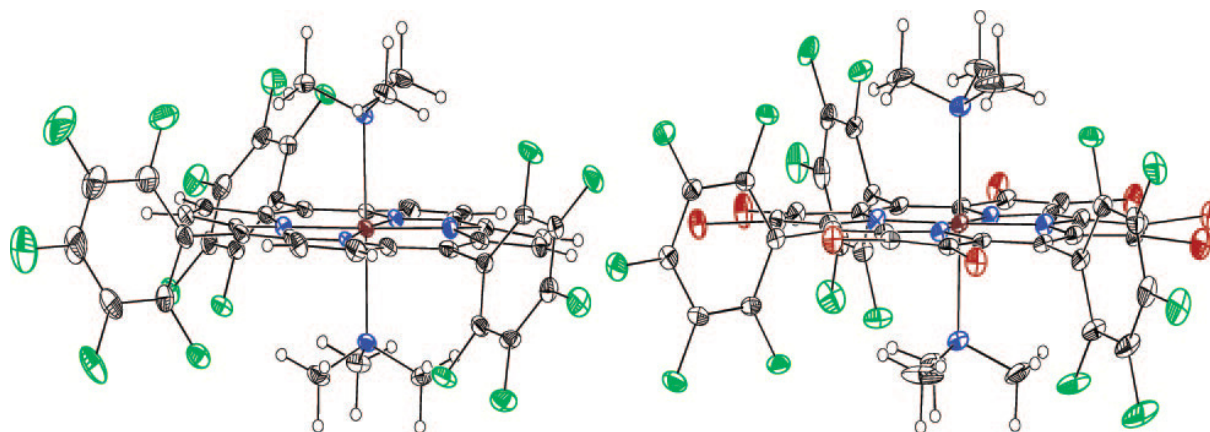

Figure 5. X-Ray crystal structures of an iridium(III) corrole (left) and its octabrominated derivative (right) show almost perfectly planar complexes.[36]

Copper corroles are inherently saddled, meaning that they adopt a saddled conformation even in the absence of peripheral steric crowding (**figure 6**).[5] Peripheral crowding increases the degree of saddling, but steric effects alone are not enough to bring about distortion from planarity. [6,7] The saddled conformation is indeed observed for all coinage metal corroles (i.e. copper[5], silver[3] and gold[40]), however it is most pronounced for copper corroles.
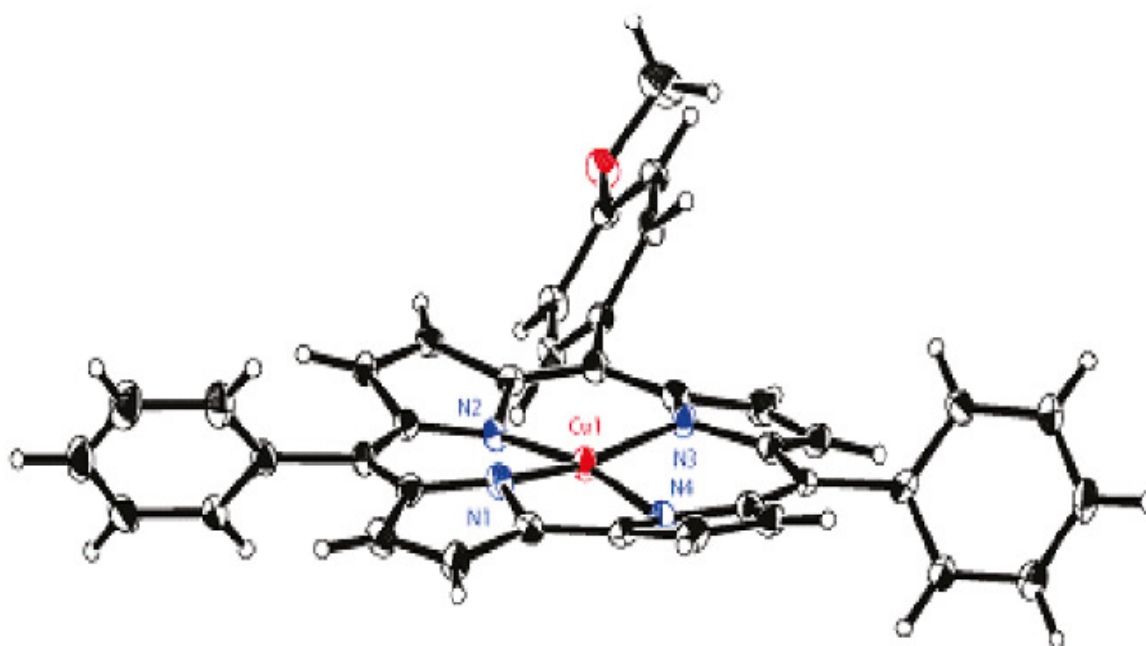
Figure 6. X-Ray crystal structure of Cu[10-(p-MeO-P)-5,15-P_2C] illustrating the copper corrole's tendency to saddle even in the absence of sterically hindering substituents.[5]

The reason for this inherent tendency originates from an orbital interaction between the formally empty copper $d_{x^2-y^2}$ orbital and the corrole π-HOMO, which becomes symmetry-allowed as the corrole saddles. Overlap of these orbitals allow for a flow of electron density (about 50%) from the corrole π-HOMO to the copper $d_{x^2-y^2}$ orbital. This interaction results in a noninnocent corrole ligand. Copper complexes of corroles cannot be described as pure Cu(III)-corrole^{3-}, as it has substantial Cu(II)-corrole$^{2-·}$ character. Both NMR[33,41] and DFT[5,33] studies predict a thermally accessible paramagnetic state of *β*-unsubstituted and *β*-fluorinated copper corroles. Complexes with larger *β*-substituents, however, do not show signs of paramagnetic states[6]. As saddling increases so does the strength of the antiferromagnetic coupling of the two unpaired electrons, and for that reason *β*-brominated and *β*-trifluoromethylated complexes are diamagnetic.[6]

An important consequence of the inherent saddling of copper corroles is that they possess lower symmetry than planar corroles. They are C_2-symmetric and thus chiral.

The Soret maxima of copper corroles are sensitive to change in substituents on the *meso*-phenyls.[34] Relative to electron-withdrawing substituents, electron-donating substituents will cause significant red-shift of the Soret maxima. As an example going from Cu[T(*p*-CF$_3$-P)C] to Cu[T(*p*-OCH$_3$-P)C] the Soret maxima will red-shift by 26 nm, from 407 to 433 nm.[34] This is also the case for MnCl and FeCl corroles,[42] but it is otherwise uncommon for metal and free-base corroles. DFT-calculations suggest that the substituent sensitivity is attributed to substantial phenyl to metal ($\pi \rightarrow d_x{}^2{}_{-y}{}^2$) charge transfer character of the Soret transitions.[34]

Liquid crystals

Liquid crystal is a state of matter that is an intermediate between the solid and liquid state as it is a liquid with degrees of orientational and translational order. The origin of the liquid crystal phases, often called mesophases, is mainly attributed to molecular structure (**figure 7**), and the molecules that form these phases are called mesogens. The calamitic or rod-like mesogens, first described in 1907 by Vorländer,[43] are long and cylindrical. Discotic or disklike mesogens are flat and circular, and were first described in 1977 by Chandrasekhar and co-workers.[44]
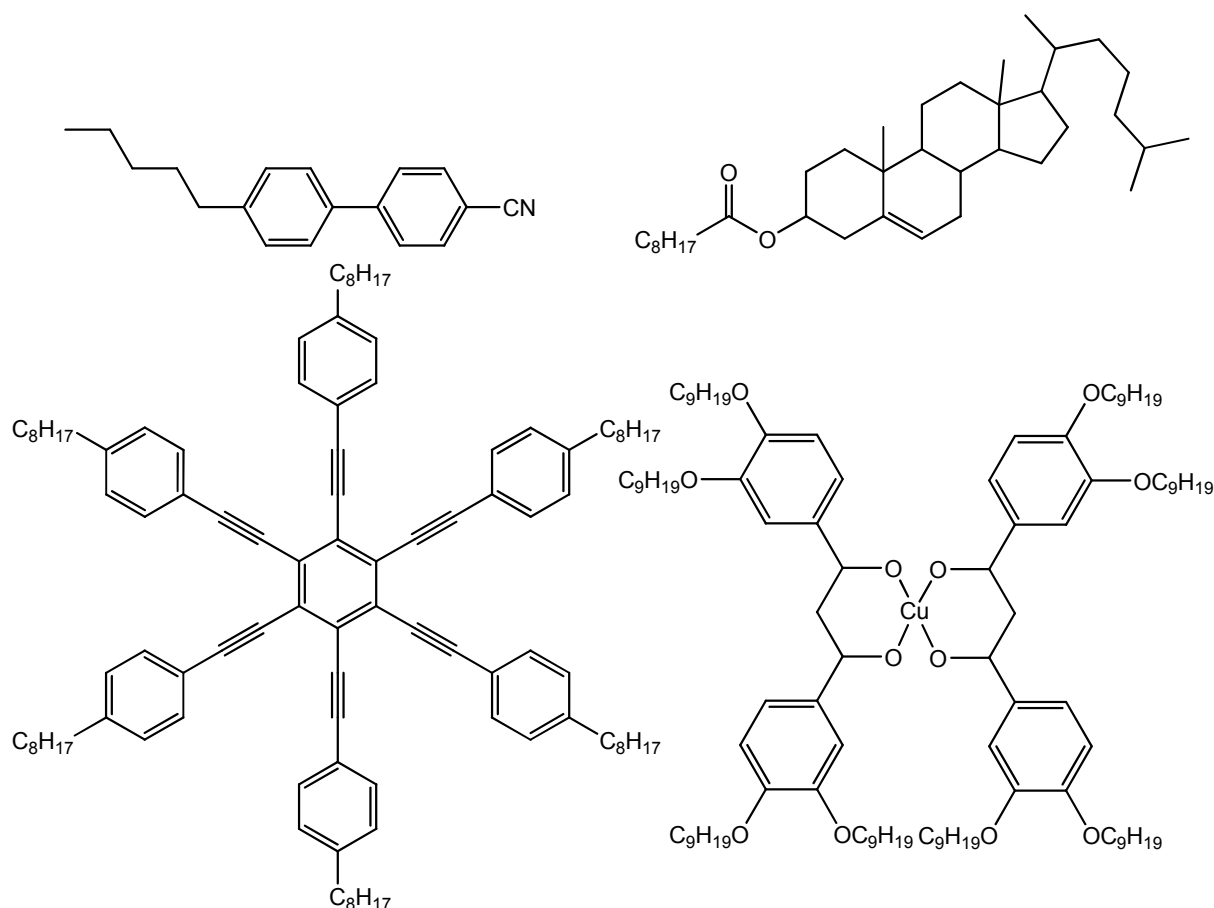

Figure 7. Examples of mesogens. The top two are calamitic and the bottom two are discotic.

The mesogens are organized into two groups, and several sub-groups. The mesogens that form mesophases as a function of temperature are called thermotropic, and the mesogens that require the influence of a solvent are called lyotropic. The calamitic and discotic mesogens mentioned above are thermotropic

mesogens. The calamitic mesophases may be nematic, smectic or cholesteric, and the discotic mesophases may be either nematic or columnar (**figure 8**).
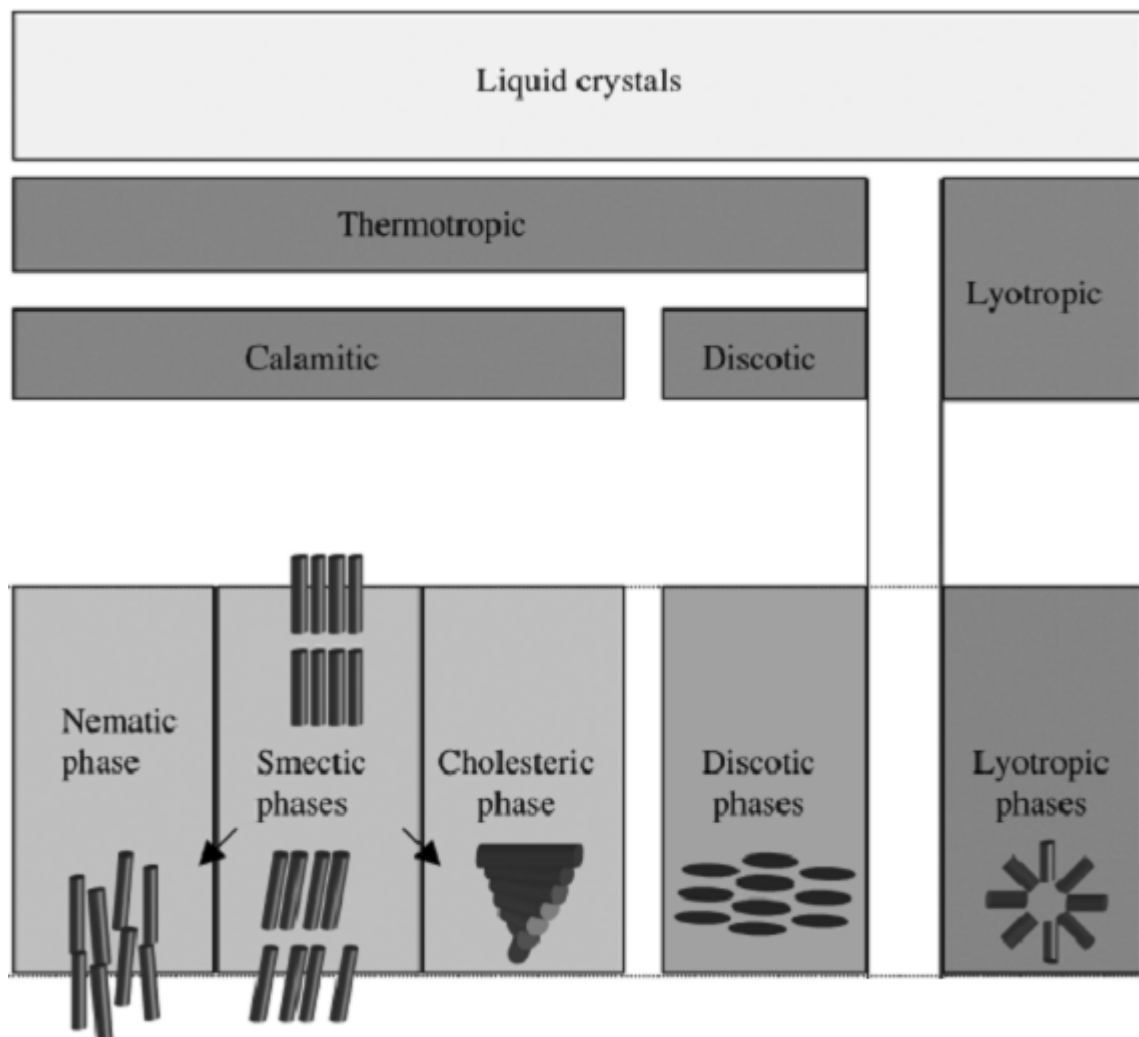

Figure 8. Liquid crystals are divided into two main groups, the thermotropic and lyotropic liquid crystals. The thermotropic liquid crystals have several sub-groups based on molecular structure and degrees of order in the liquid crystal phases.[45]

Thermotropic mesophases occur above the melting temperature of a pure solid when molecular motion is slow and intermolecular forces are strong compared to thermal energies. As the temperature increases the liquid crystal may undergo further phase changes, often to less ordered mesophases, before finally all intermolecular forces are broken and the liquid crystal melts to an isotropic liquid.

The nematic phase (**figure 9a**) is characterized by a high degree of orientational order, but no translational order (i.e. the molecules all point in the same direction, but may slip along the orientation axis). The nematic phase is the least ordered of calamitic mesophases, and in mesogens forming several mesophases it is usually the last phase to occur before melting to an isotropic liquid. The degree of order in a calamitic mesophase is given by a parameter, S, which represents the rotational freedom of the calamitic mesogen perpendicular to its own rod-like axis. An S of 1 represents a perfectly ordered nematic phase, and an S of 0 represents an isotropic liquid.
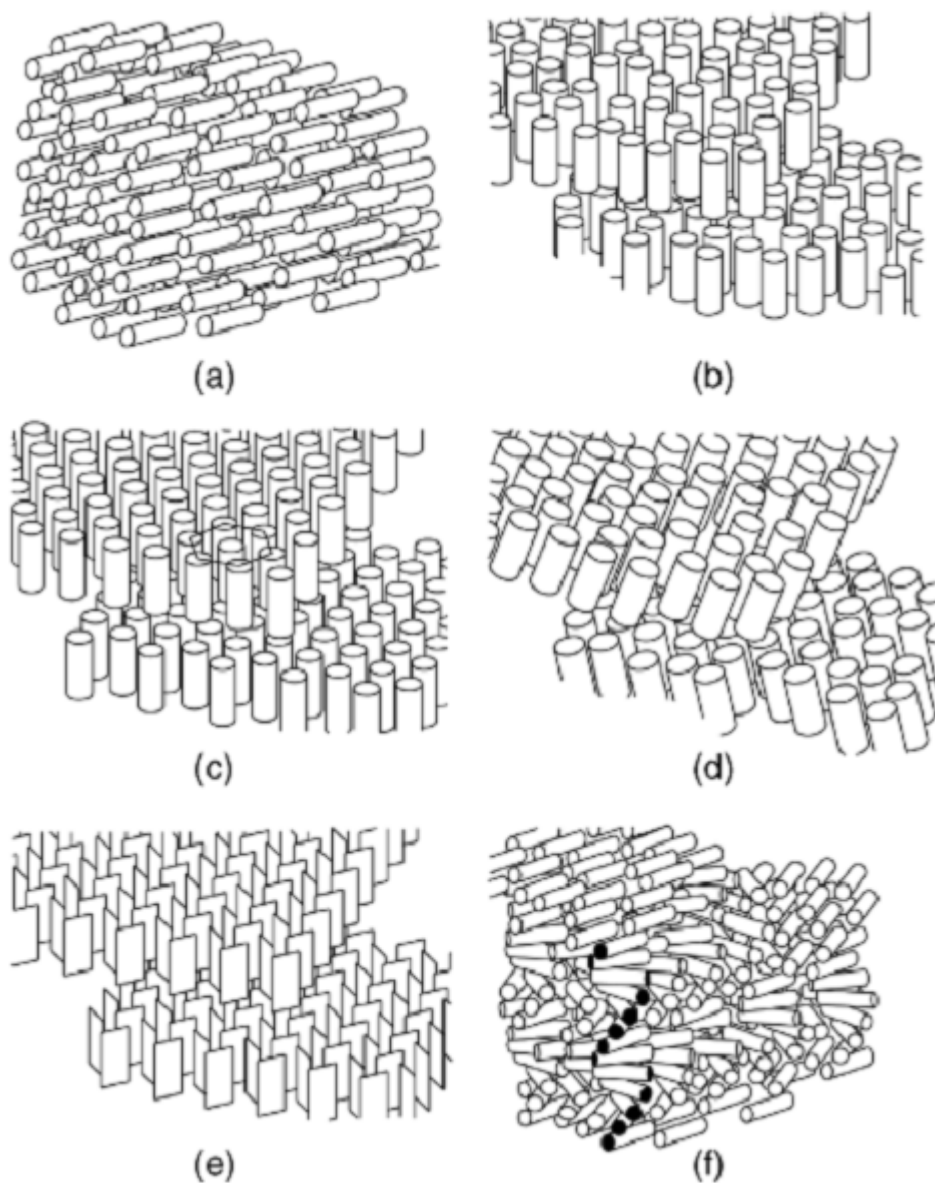

(a)   (b)

(c)   (d)

(e)   (f)

Figure 9. Illustrations of the calamitic mesophases: (a) nematic, (b) smectic A, (c) smectic B, (d) smectic C, (e) smectic E and (f) cholesteric.[45]

The smectic phases represent a higher degree of order than the nematic phase. They are organized as two-dimensional layers, in which they have orientational order and various degrees of translational order. Interactions between layers are limited, allowing them to slip easily with respect to their neighbours. Within a layer there are various degrees of order. Smectic A and C (**figures 9b and 9d**) are examples of less ordered smectic phases where the mesogens are unevenly distributed in the layer, allowing the mesogens to move about in the layer and giving them rotational freedom, and where layers are tilted with respect to each other. Smectic B and E (**figures 9c and 9e**) are examples of highly ordered smectic phases. The smectic B has the mesogens arranged in a hexagonal pattern, and for flat mesogens a herringbone arrangement is possible as in the smectic E phase. A total of 12 different smectic phases have been characterized, where the most ordered phases are highly viscous liquids.

Cholesteric phases (**figure 9f**) are a kind of helical nematic phase, where the mesogens instead of lining up in parallel change their orientation with respect to one another to appear as a helix. The cholesteric phase is chiral, and also known as the chiral nematic phase. It is possible to generate cholesteric phases from ordinary nematic phases by adding nonmesogenic chiral molecules to the nematic phase.

The discotic phases fall into two types: the nematic and the columnar phase. The columnar phase is constructed by stacking disks on top of one another to columns, forming a lattice (**figure 10a**) due to order between the columns. The flat core of the mesogen may be replaced by a conical one, and if it is hollow at the centre it is referred to as a tubular mesophase. The nematic phase is less ordered, with the mesogens showing orientational order, but no translational order (**figure 10b**).
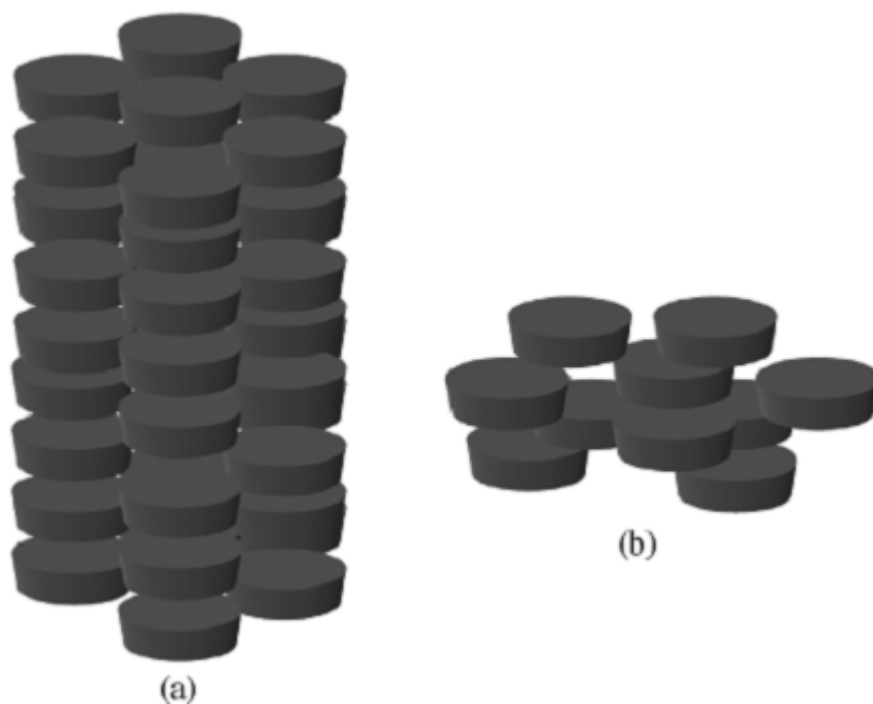
Figure 10. Illustrations of the discotic mesophases: (a) columnar and (b) nematic.[45]

Lyotropic mesophases are made up of two or more components. One is usually an amphiphile (i.e. a molecule with hydrophobic and hydrophilic moieties). The other one is usually water, or occasionally another solvent. Various phases may occur depending on the amphiphile concentration, but high concentrations are usually required to bring about intermolecular interactions and formation of the mesophase. Typical lyotropic mesogens are biological molecules like lipids that form micelles, vesicles, bilayers etc in the presence of water.

Liquid crystals have a number of applications. Calamitic mesogens are well known for their performance in liquid crystal displays. Discotic mesogens will never rival their calamitic counterparts in terms of optical performance, but as a result of their assembly into columnar stacks they act as molecular wires and have a number of possible applications in electronic devices such as organic solar cells[46,47] and organic light emitting diodes.[48,49]

Porphyrin based liquid crystals

Porphyrin based liquid crystals have been known since 1980,[50] and since then a number of porphyrins exhibiting mesophases have been synthesized. The basic architecture for constructing liquid crystal porphyrins has been to introduce long alkyl chains around the periphery of the porphyrin core, these may be positioned at the *β*-positions,[51,52] the *meso*-positions[53] or as substituents on *meso*-phenyls[54] (**figure 11**). The flat aromatic cores stack on top of one another and the alkyl chains provide fluidity.
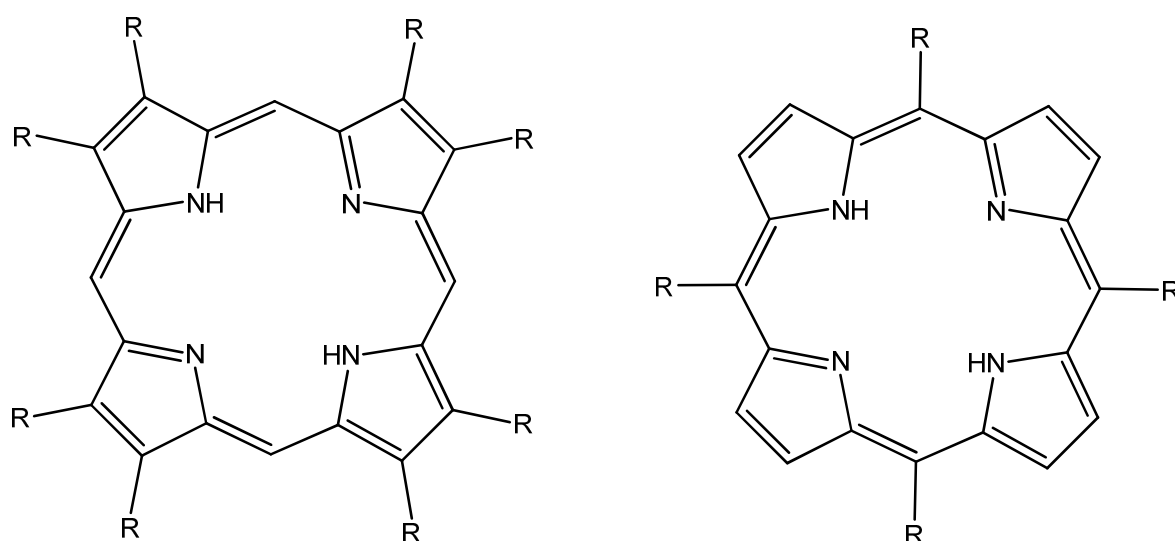

Figure 11. Examples of liquid crystals porphyrin architecture.

Liquid crystal porphyrins have applications in organic photovoltaics. Thin films of liquid crystal porphyrins can be sandwiched between two indium-tin oxide electrodes and produce a current when irradiated. [55,56] The group of Fox also showed that if zinc-octakis(decoxyethyl)porphyrin (**figure 12**) was placed between the two indium-tin oxide electrodes the cell could be used for optical data storage.[57]
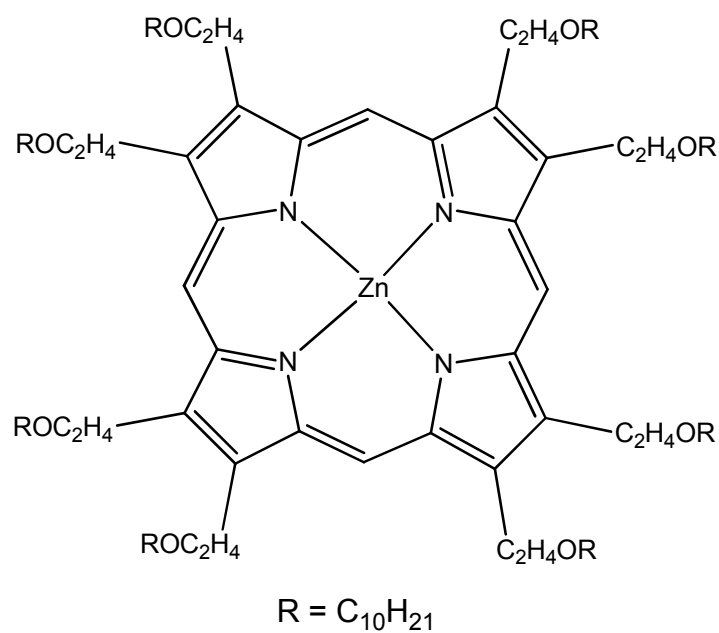
$R = C_{10}H_{21}$

Figure 12. Zinc-octakis(decoxyethyl)porphyrin used for optical data storage.

A major challenge concerning the practical use of discotic liquid crystals is being able to control the alignment of columns and to create large area films with uniformly aligned columns. Li *et al* addressed this issue by synthesizing a liquid crystal porphyrin with partially fluorinated alkyl chains (**figure 13**).[58] The fluorinated liquid crystal proved far better at self-assembling into uniformly aligned films then its non-fluorinated counterpart.
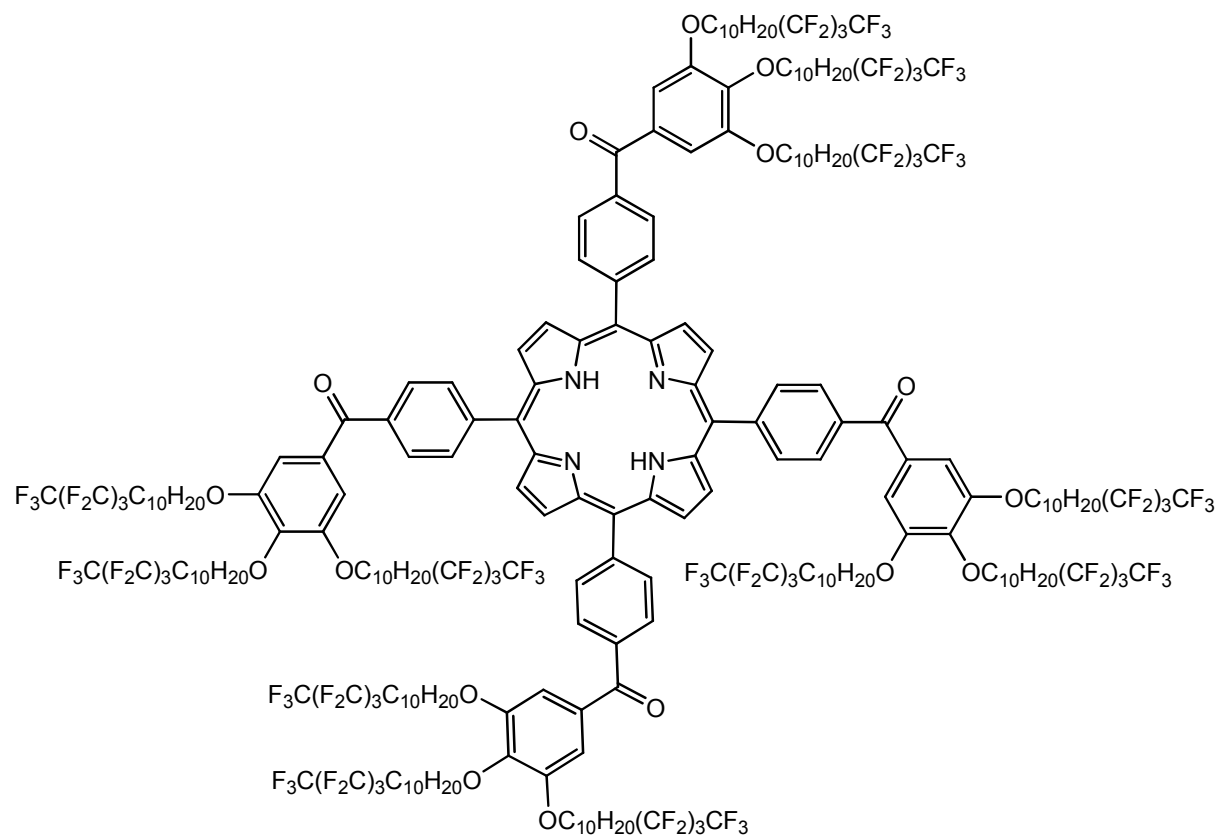
Figure 13. A fluorinated liquid crystal porphyrin that excelled at self-assembling.

Isolation of a new porphyrinoid, possibly an isosmaragdyrin

The initial goal of this thesis has been to functionalize corroles with fluorous tags (i.e. partially fluorinated alkyl chains) at either the *β*-positions or the *meso*-phenyls (**figure 14**). The hope was that these corroles would possess discotic liquid crystal phases, which would make them potential candidates for a number of different devices relying on materials with good electron transporting capabilities (e.g. solar cells, light emitting diodes and optical data storage).
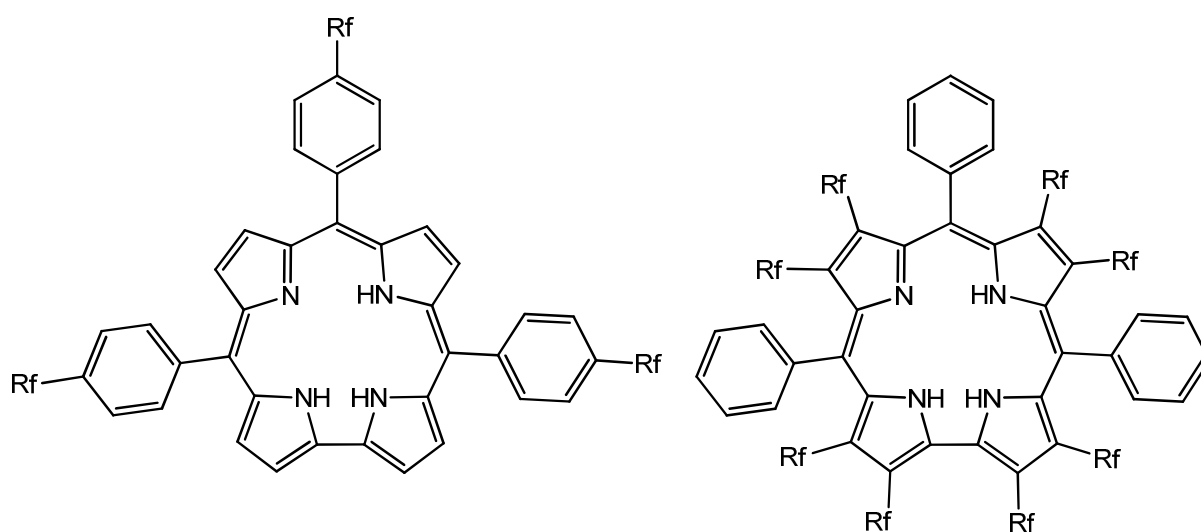

Figure 14. The two target molecules of this thesis.

Initial attempts at condensing a fluorous tagged aromatic aldehyde with pyrrole using Gryko`s method failed, as the highly fluorinated aldehyde was not soluble in the reaction medium. To overcome this problem I adjusted the water/methanol ratio and a ratio of 1:5 (water/methanol) was found to be the solvent with the highest content of water capable of dissolving the aldehyde. This slightly modified procedure worked and indeed the reaction yielded the desirable corrole. The yield of the corrole was poor however, and an "impurity" of +66 mass (relative to the corrole) appeared as the major product of the reaction, and isolating the corrole from this "impurity" was extremely difficult. I attempted to vary several parameters of the reaction (e.g. solvent ratio and reaction time), until I eventually realized that +66 mass corresponded to an extra pyrrole unit, possibly incorporated into the macrocycle itself.

I turned my attention to the new macrocycle and it proved to be a lot easier to synthesize and purify. By condensing the fluorous tagged aldehyde and pyrrole overnight, followed by oxidation with DDQ for an hour and a half I obtained the free-base in yields up to 5,9%. I also inserted copper into the free-base using standard conditions for copper insertion on corroles. The reaction worked and proceeded in yields as high as 85%.

Macrocycles containing five pyrrole units and three *meso*-carbons are known as smaragdyrins. They come in two isomers, smaragdyrin and isosmaragdyrin (**figure 15**). The mechanism of my reaction indicates that I have synthesized the isosmaragdyrin. The bilane (i.e. the corrole precursor) is present in the reaction mixture prior to oxidation meaning that the fifth pyrrole unit will most likely incorporate itself into the macrocycle between the two terminal pyrrole units of the bilane. The flourous tags on the periphery of the macrocycle may be what allow this reaction to happen. The fluorous tags may cause the bilane to orient itself like a discotic liquid crystal, bringing the two terminal pyrrole units close to each other. The excess pyrrole of the reaction may then position itself in between the two terminal pyrroles, possible by hydrogen-bonding or other interactions, creating a templating effect.
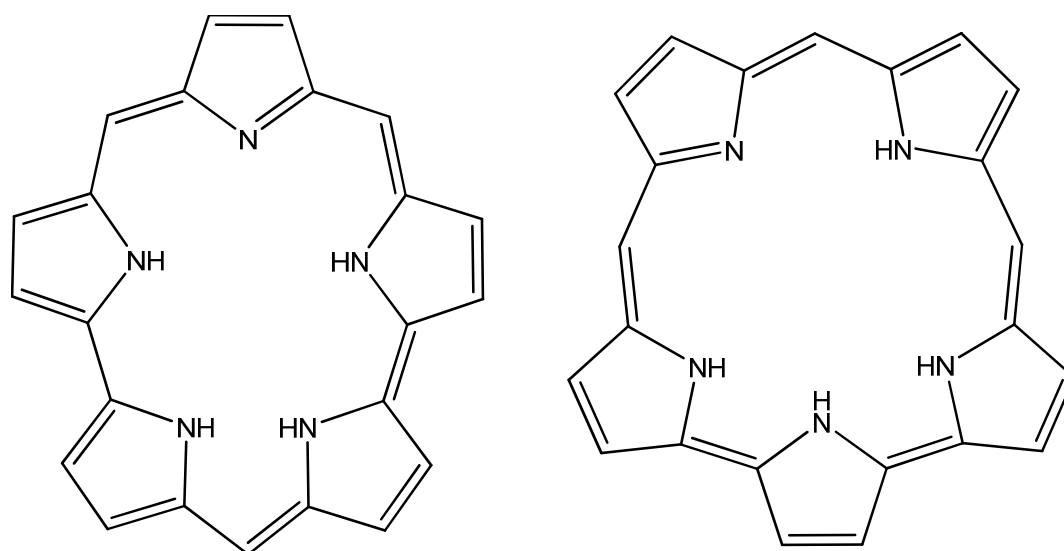

Figure 15. Smaragdyrin (left) and isosmaragdyrin (right).

The UV-visible spectrum of the free-base shows a broad soret-band with a maxima at 415 nm. The copper complex displays an even broader soret band, with a maxima at 468 nm. Both compounds absorb light in the higher wavelengths as well, the free-base absorbs light over the entire 600-800 nm region, and the copper complex absorbs in the 650-950 nm region. The increased absorptions are indicative of a larger conjugated π-system, consistent with the fifth pyrrole unit being incorporated into the macrocycle.

^{1}H and COSY-NMR spectra of the free-base show a large number of signals in the aromatic region. A minimum of ten phenyl protons are observed, and a number of signals that may be attributed to *β*-protons, but possibly also NH-protons in the core. The high number of signals may indicate a chiral compound, or the synthesis may yield a mixture of isomers.

The ^{1}H-NMR of the copper complex show broad signals, and compared to the free-base most signals are missing, a clear indication of a paramagnetic compound. If this is the case, then it raises several interesting questions. Is the macrocycle dianionic, forming stable copper(II)complexes, or is it like the corrole a non-innocent ligand which funnels electron density into empty orbitals of the copper. If the latter is true, then there may be other consequences to the macrocycle, like non-planarity in the case of corrole.

Based on the above evidence, I propose two isosmaragdyrins as possible structures of the synthesized compounds (**figure 16**).
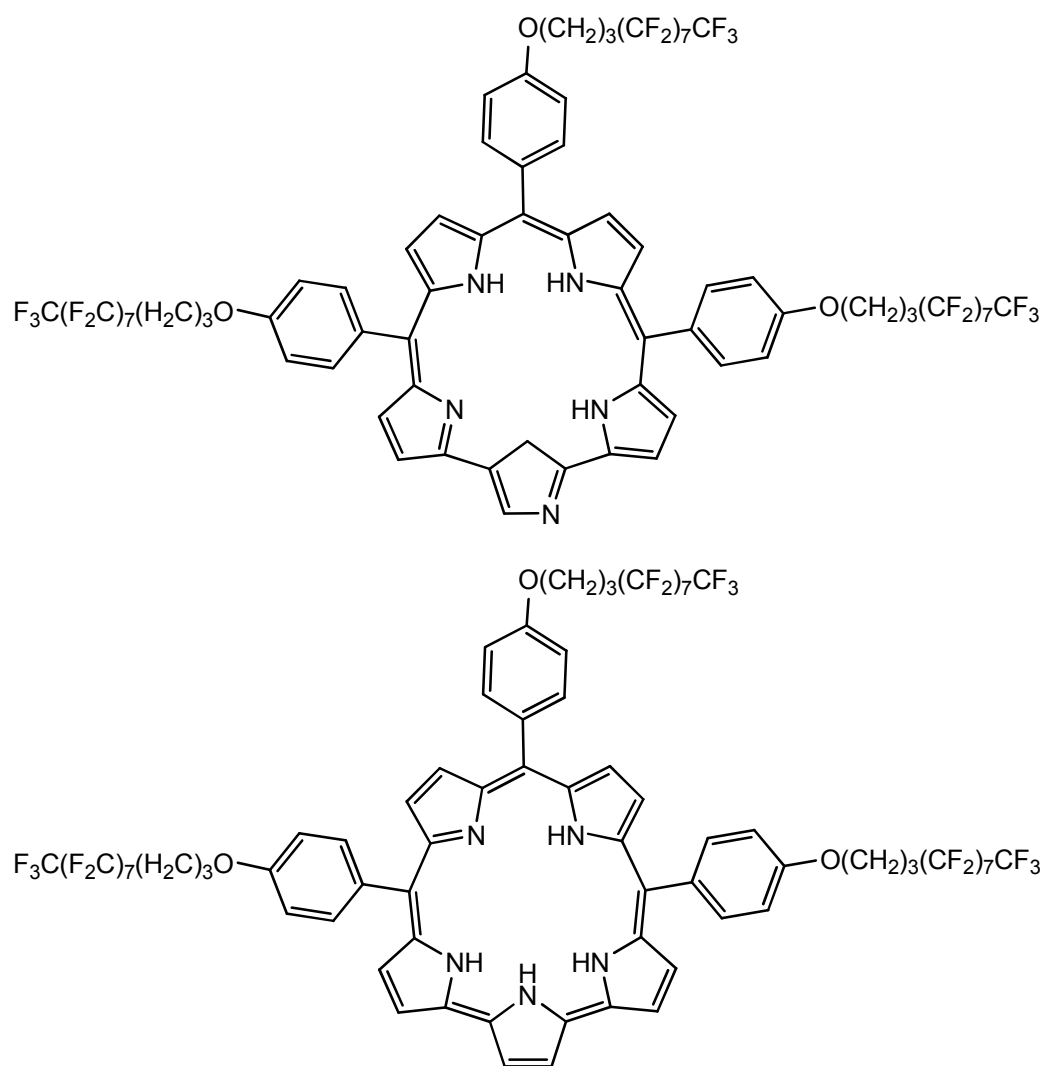
Figure 16. Two possible structures of the synthesized compound.

Concluding remarks

I have isolated a new porphyrinoid from the pyrrole-aldehyde condensation, expanding the scope of the reaction and illustrating how the pyrrole-aldehyde condensation indeed may yield a variety of macrocycles, simply by tuning the reaction conditions. The free-base and copper complex of the porphyrinoid have been synthesized and characterized by NMR, UV-vis and MS spectroscopy.

The porphyrinoid is a macrocycle containing five pyrrole units and three *meso*-carbons, and based on spectroscopic evidence I believe it is an isosmaragdyrin, although further work is needed to ascertain its structure.

UV-vis spectroscopy reveals that both compounds absorb impressive amounts of light, especially the copper complex which absorb light in almost the entire 300-1000 nm region.

NMR of the copper complex is a clear indication of a paramagnetic compound, an intriguing possibility that needs further investigation.

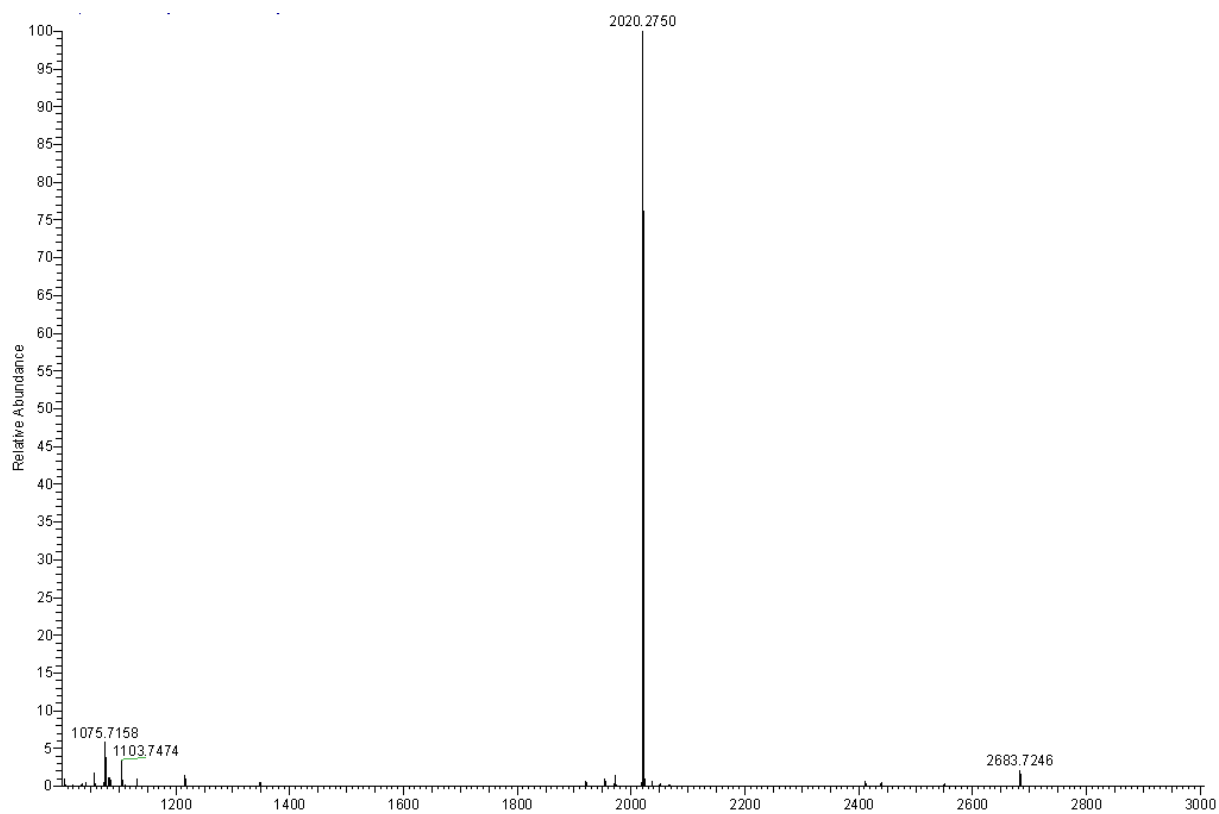I hope to pursue working on these new compounds during a potential PhD.

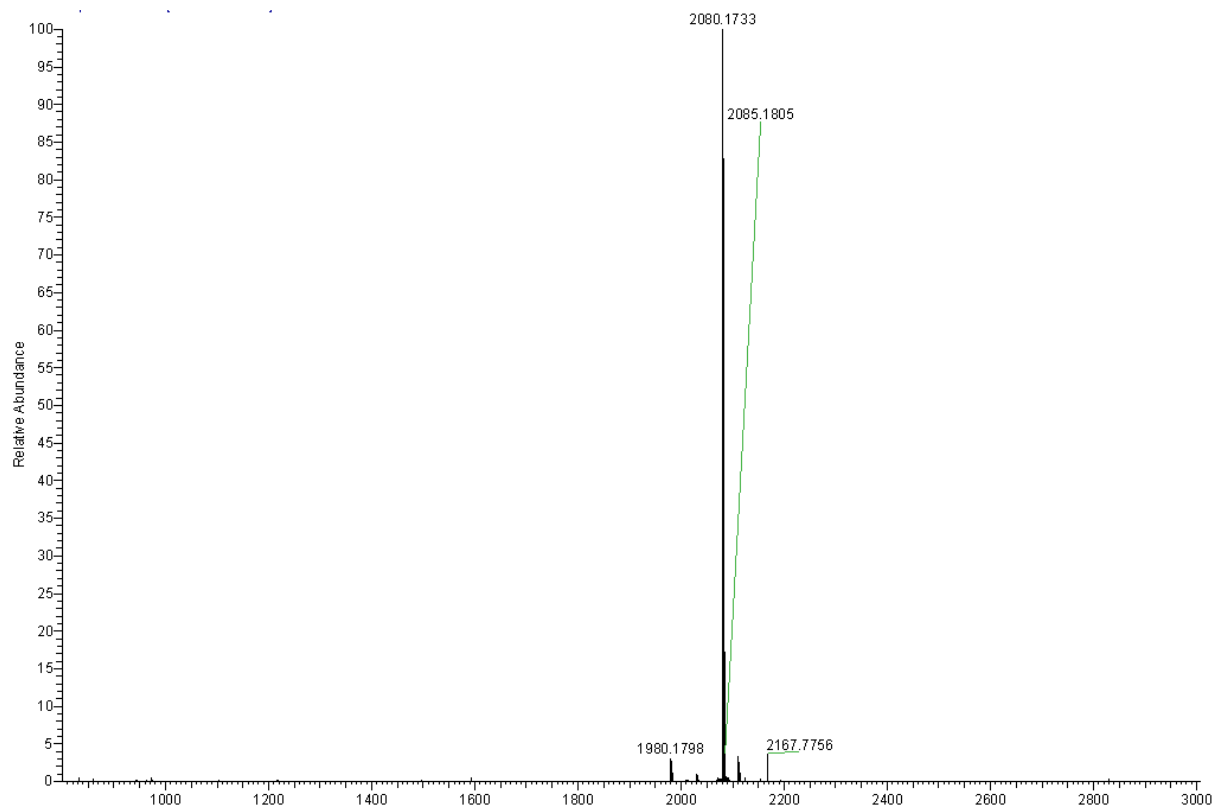**Figure 17.** ESI-MS spectrum of the free-base.

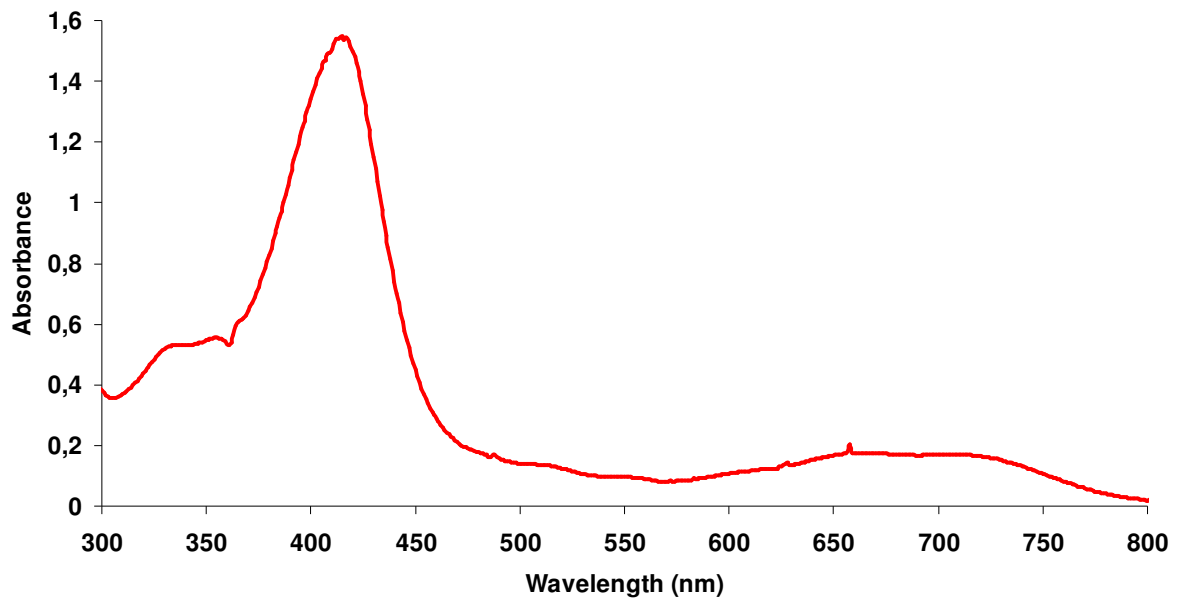**Figure 18.** ESI-MS spectrum of the copper complex.

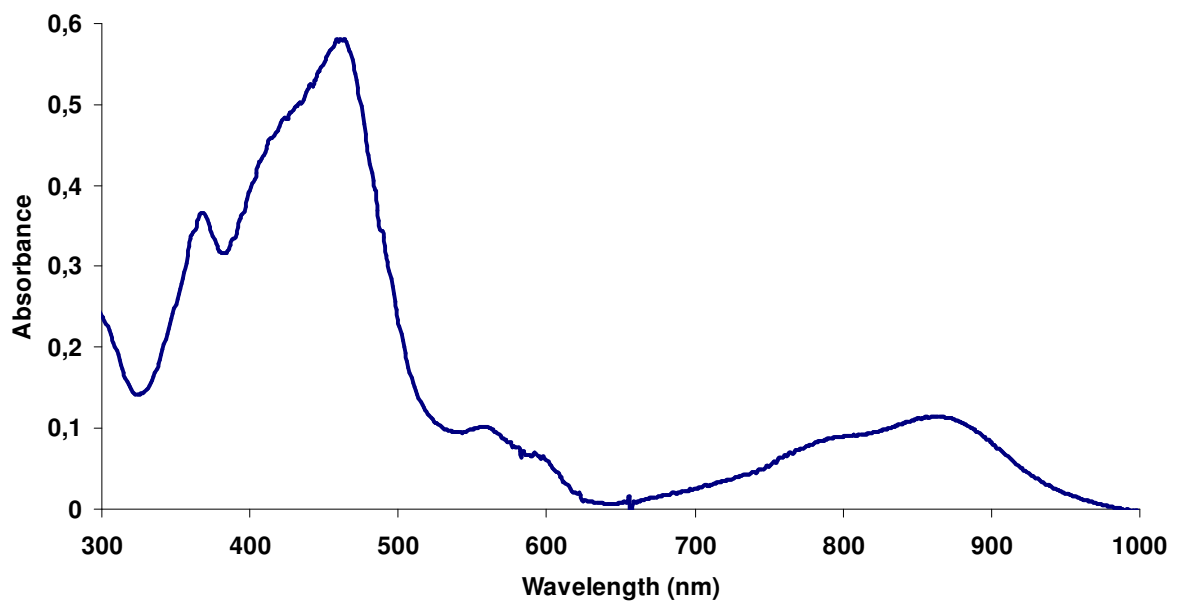**Figure 19.** UV-visible spectrum of the free-base.

Figure 20. UV-visible spectrum of the copper complex.
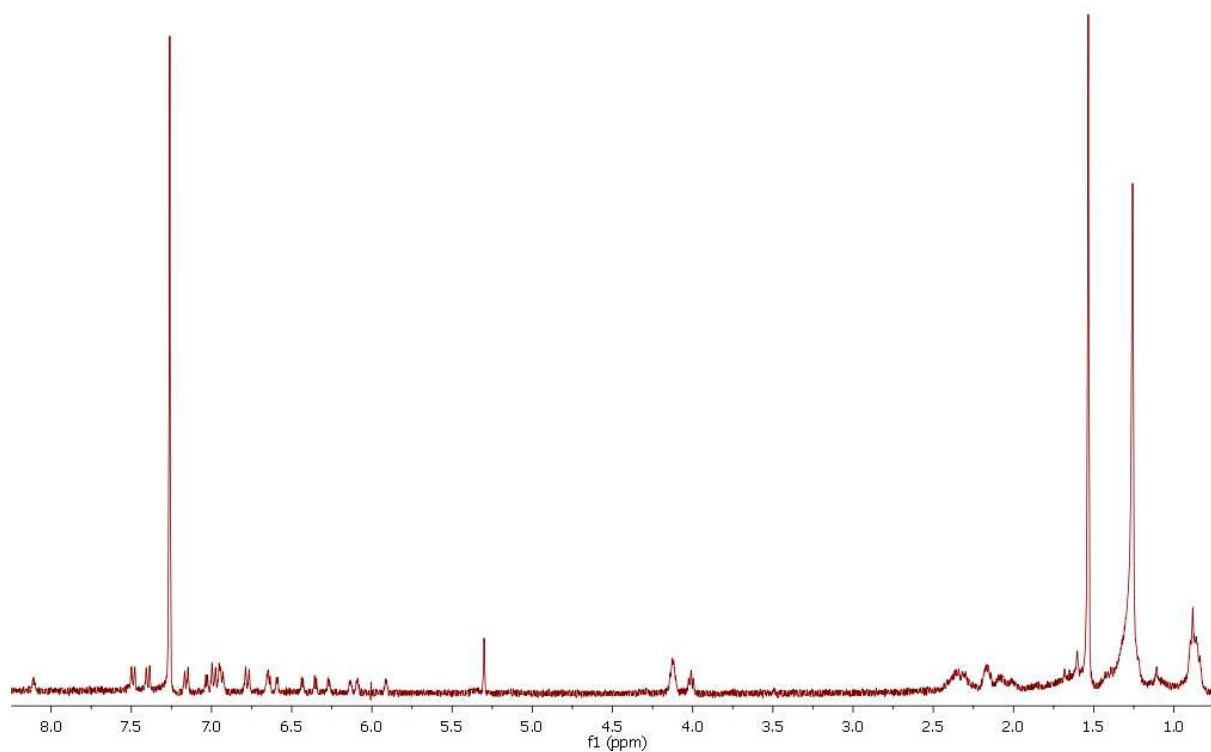
Figure 21. ^{1}H-NMR spectrum of the free base.
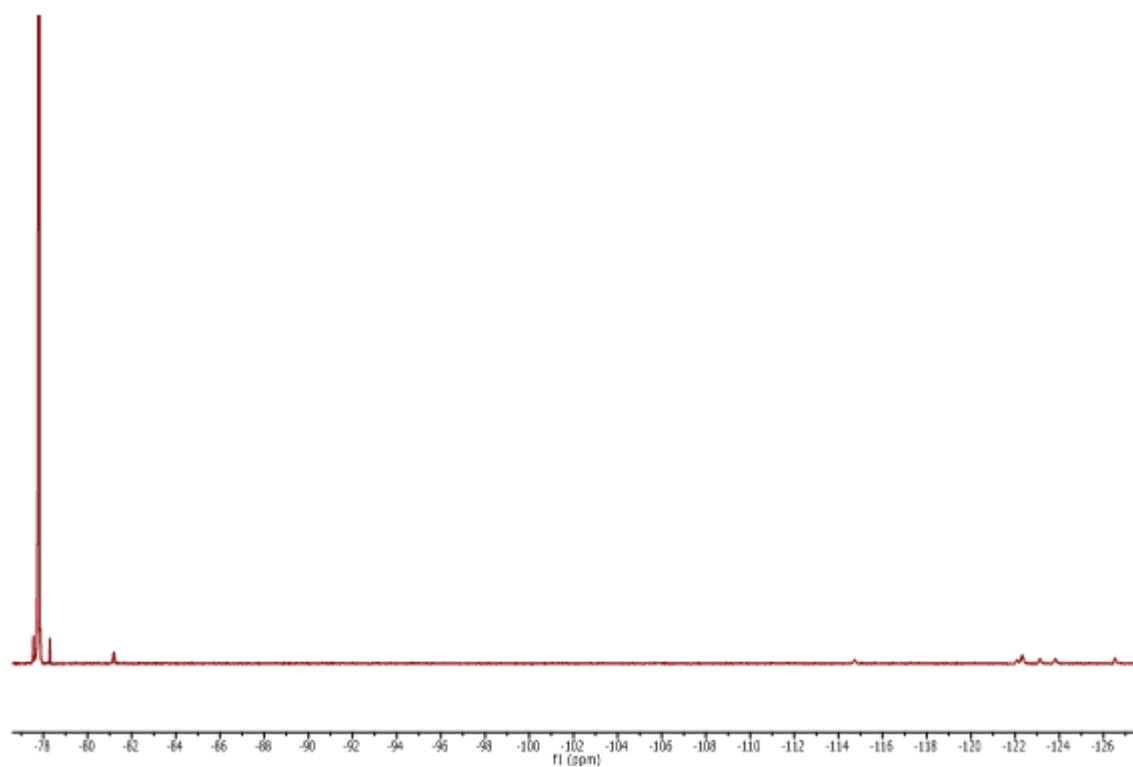
Figure 22. ^{19}F-NMR spectrum of the free base.
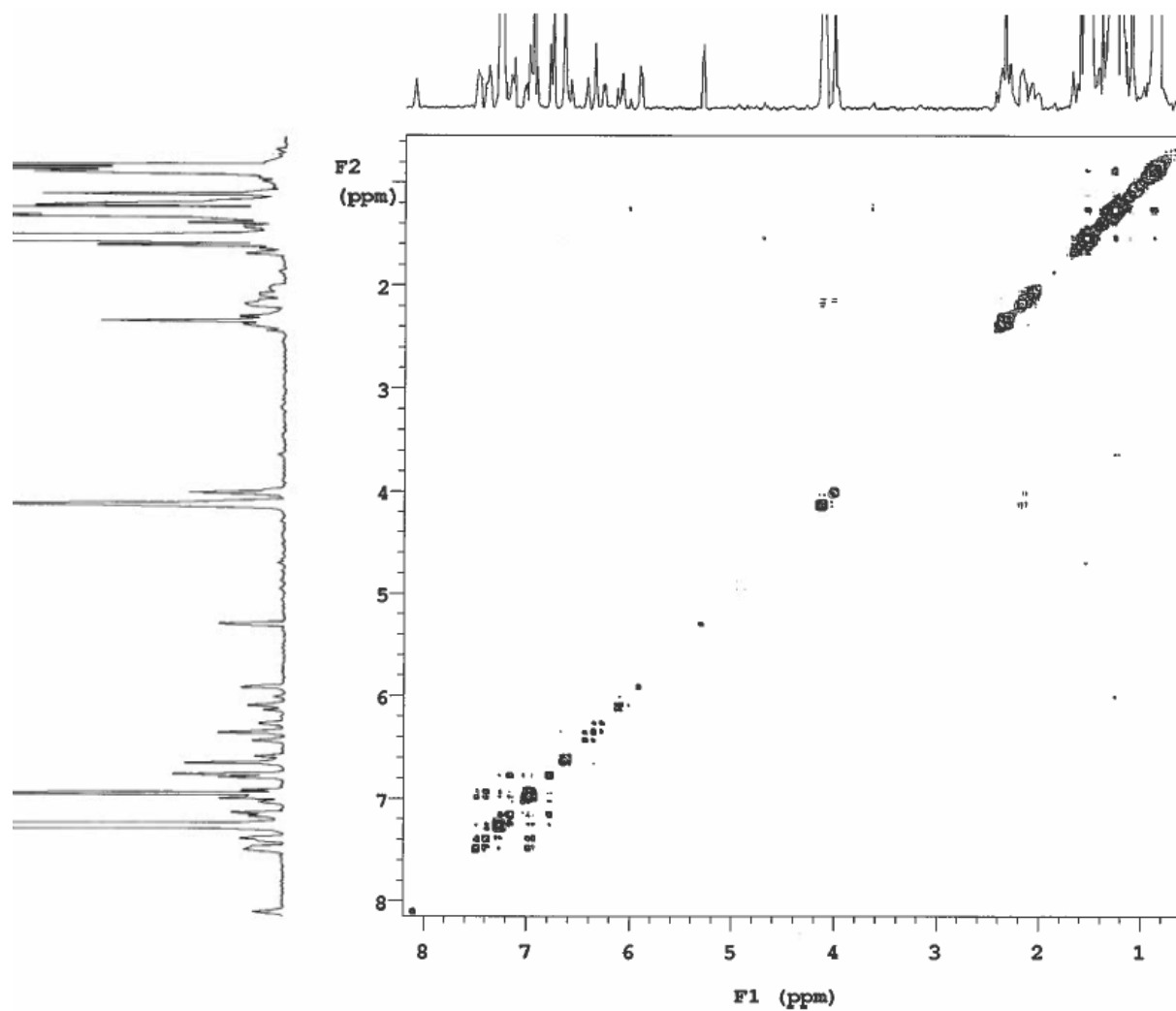
Figure 23. COSY-NMR spectrum of the free-base.
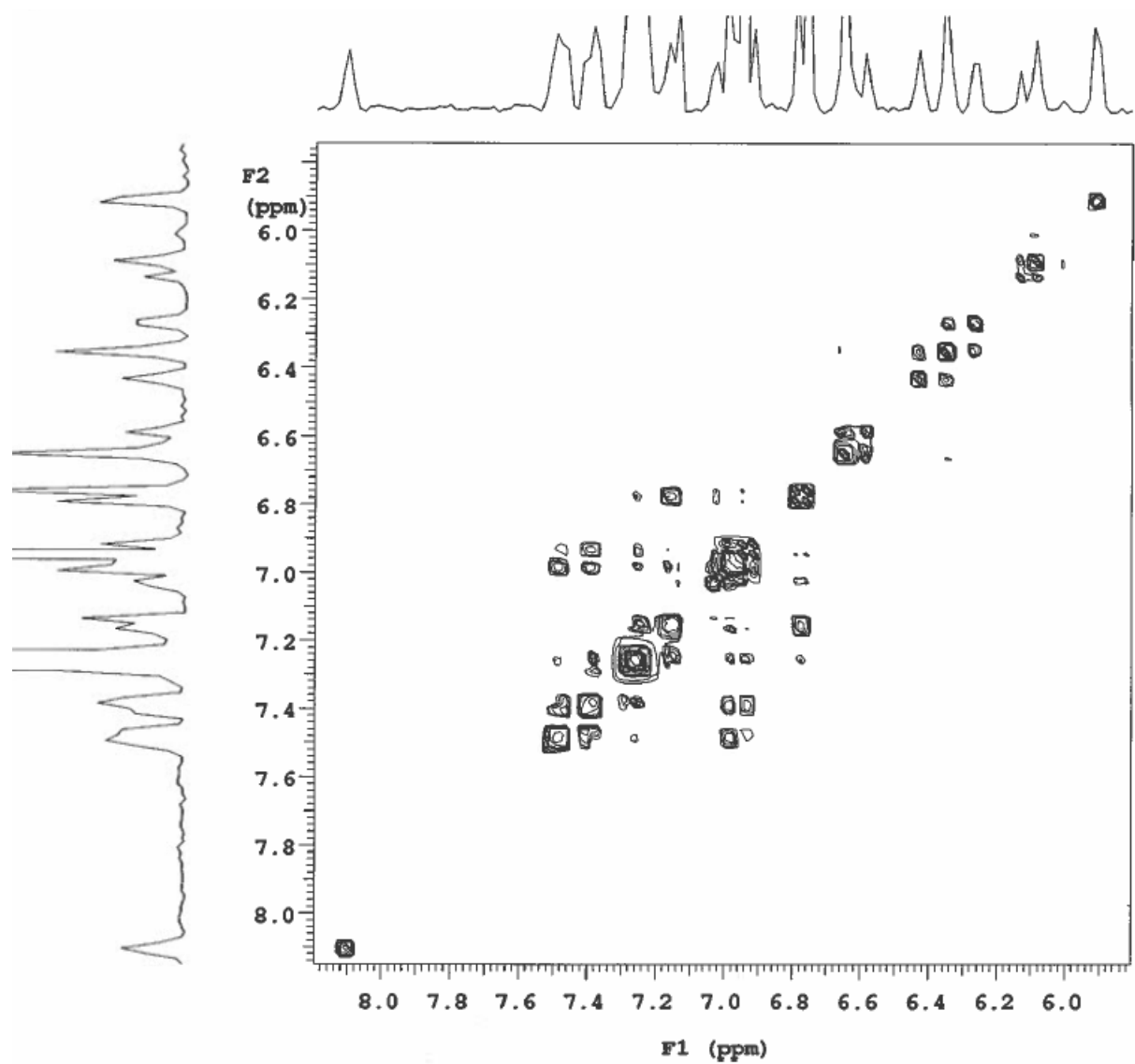
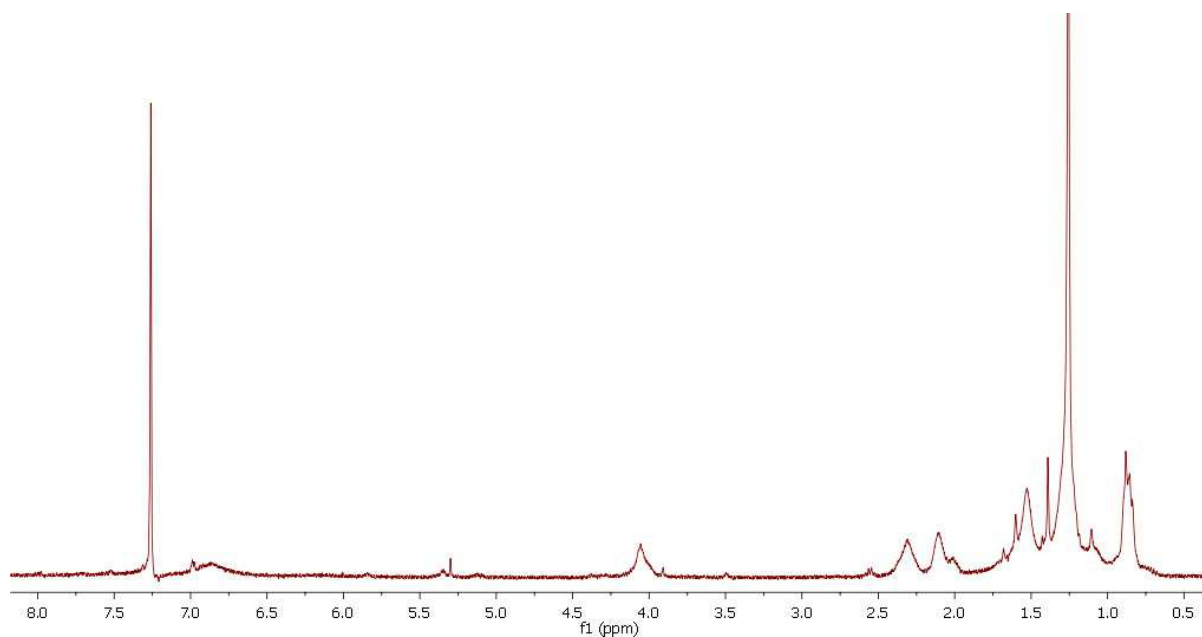**Figure 24.** COSY-NMR spectrum of the free-base, aromatic region expanded.

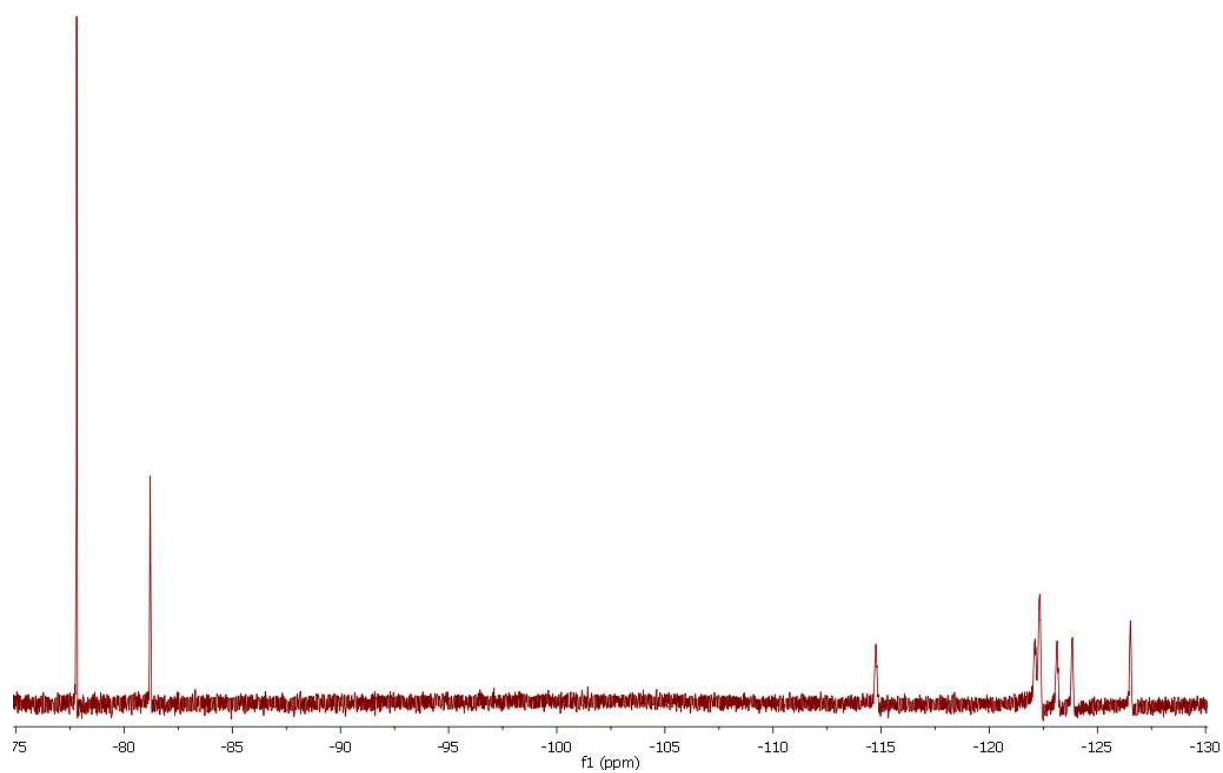**Figure 25.** ^{1}H-NMR spectrum of the copper complex.

Figure 26. ^{19}F-NMR spectrum of the copper complex.

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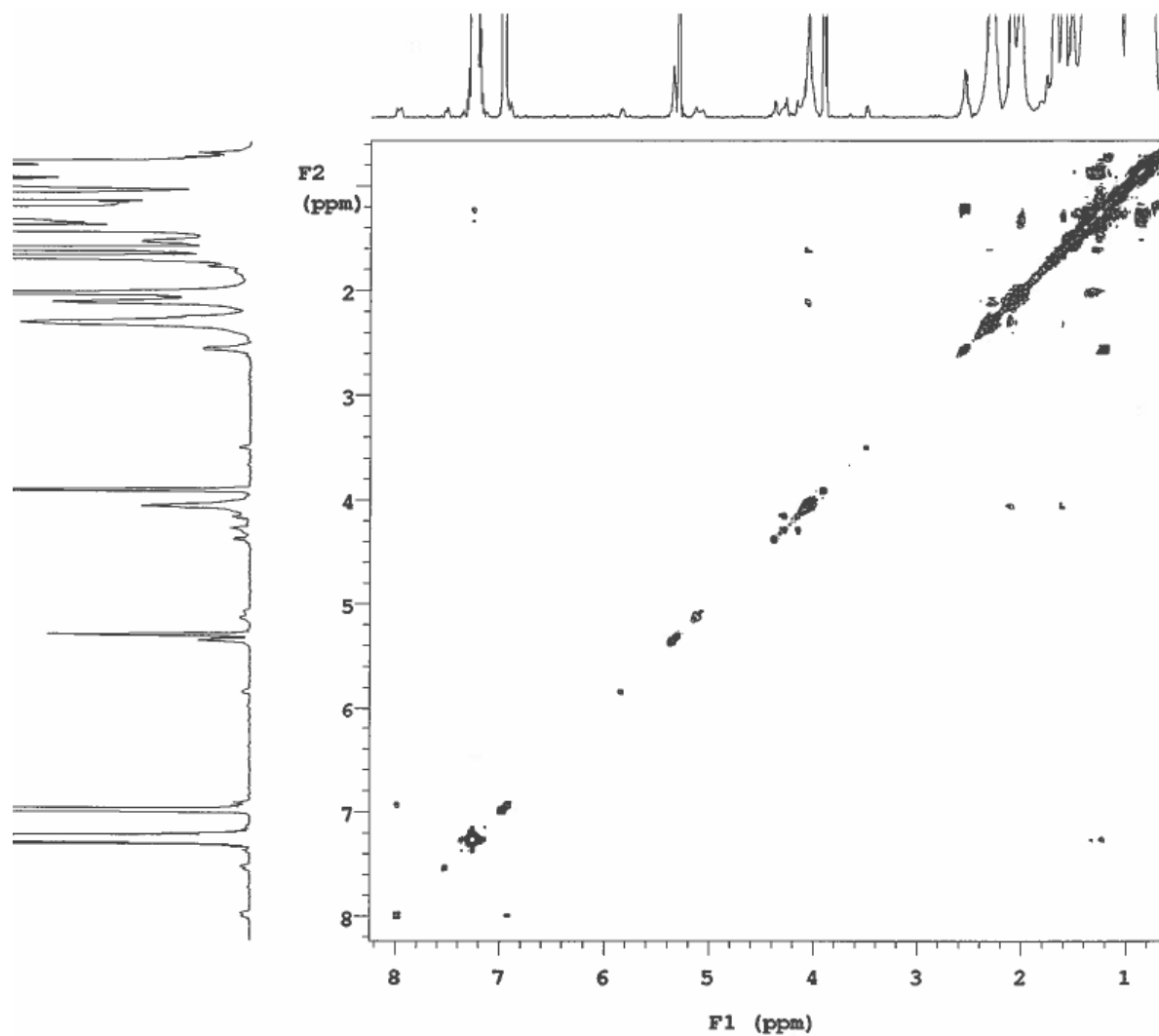
Figure 27. COSY-NMR spectrum of the copper complex.
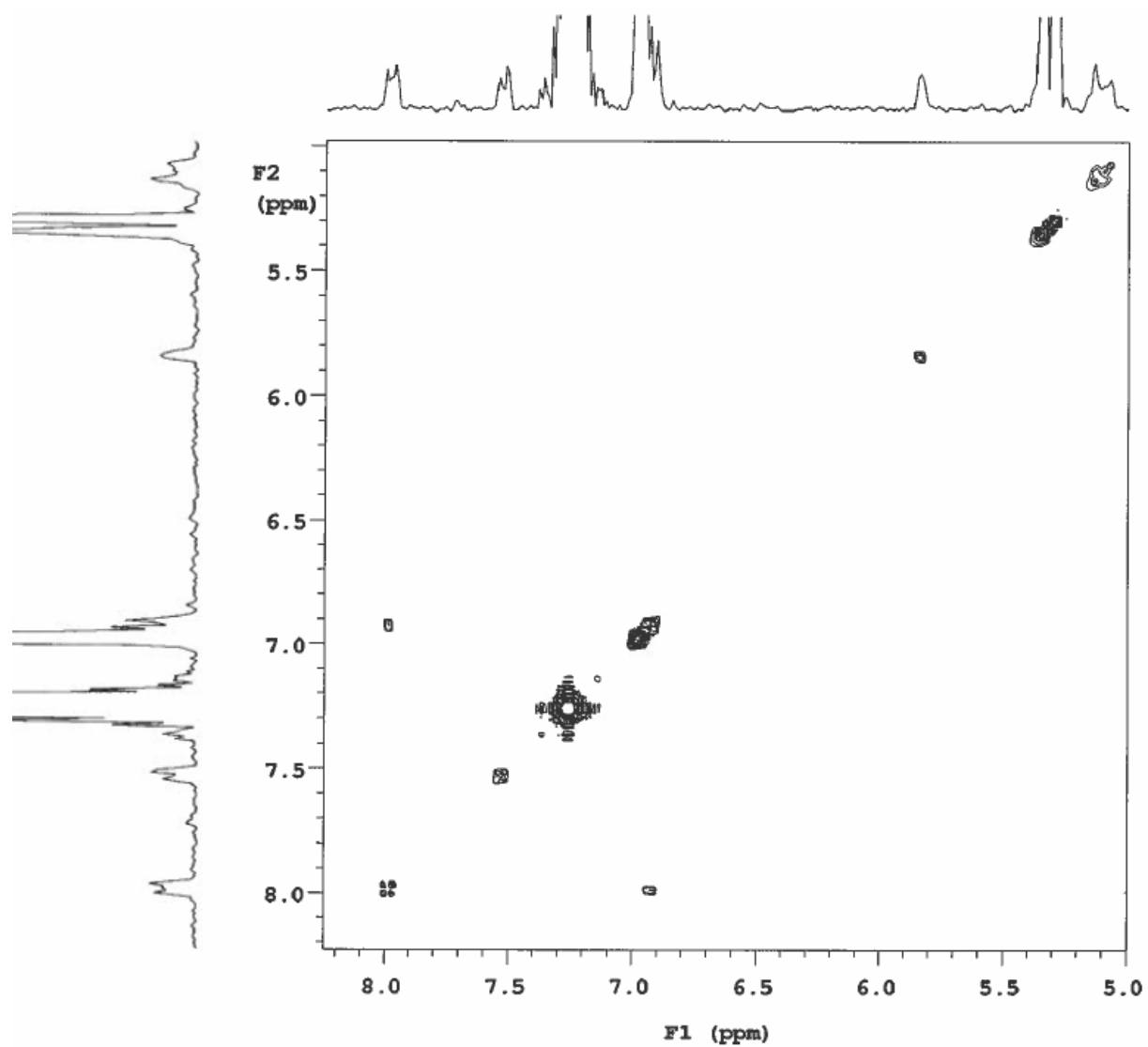
Figure 28. COSY-NMR spectrum of the copper complex, aromatic region expanded.

Materials and reagents

All reagents and solvents were used as purchased, except pyrrole which was distilled and stored in a freezer under argon. Silica (DAVISIL LC150A 35-70 µm) was used for flash chromatography. Silica gel 60 preparative thin-layer chromatography (TLC) plates (20 cm x 20 cm, 0.5 mm thick, Merck) were used for purification of compounds for characterization purposes. All samples for NMR analysis were prepared in 5 mm NMR tubes using $CDCl_3$, and recorded with a Varian 400 MHz spectrometer at room temperature. ^{1}H- and COSY-NMR spectra were referenced to residual $CHCl_3$ (δ = 7.26 ppm), ^{19}F-NMR spectra were referenced to 2,2,2-trifluoroethyl alcohol-d_3 (δ = -77,8 ppm). Ultraviolet-visible spectra were recorded on an HP 8453 spectrophotometer with CH_2Cl_2 as solvent. ESI-MS spectra were recorded on an LTQ Orbitrap XL using MeOH as solvent.

Experimental

Synthesis of the free-base:

4-(4,4,5,5,6,6,7,7,8,8,9,9,10,10,11,11,11-Heptadecafluoroundecyloxy)-benzaldehyde (288,7 mg) and pyrrole (70 µl) were dissolved in MeOH (33 ml), and H_2O (6 ml) was added. Subsequently HCl_{aq} (37%, 425 µl) was added, and the reaction was stirred at room temperature overnight. The reaction mixture was extracted with $CHCl_3$ (30 ml), washed twice with H_2O and dried (Na_2SO_4). DDQ (113,5 mg) was added and the mixture was stirred at room temperature for 1,5 h. The reaction mixture was passed over a silica column (CH_2Cl_2) and the first green fraction was collected, a subsequent column (CH_2Cl_2/*n*-hexane 1:1) yielded 18,7 mg (5,9%). Further purification for characterization purposes was performed by preparative-TLC (CH_2Cl_2/*n*-hexane 1:1).

Synthesis of copper complex:

Free-base (20.2 mg) and $Cu(OAc)_2$ (50 mg) was dissolved in pyridine (5 ml) and stirred at room temperature for 1 hour. The reaction mixture was passed over a silica column (CH_2Cl_2) and the first brown fraction was collected. The solvent was evaporated yielding 17,7 mg (85%). Further purification for characterization purposes was performed by preparative-TLC (CH_2Cl_2), then (CH_2Cl_2/*n*-hexane 1:1).

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