

Abstract

DAWN-ALITA ROBERTS. Synthesis and Characterization of Two Tetraarylporphyrins with Highly Electron-Withdrawing Substituents. (Under the Direction of Dr. AVRAM GOLD.)

The proposed intermediate for the heme-enzymes, cytochrome P-450, horseradish peroxidase, and chloroperoxidase, is an oxoferryl porphyrin π -cation radical. Therefore, iron porphyrins are used to study heme-enzymes and to study the influence of substituents on physicochemical properties of the porphyrin macrocycle. Spin-spin coupling (between the ferryl iron unpaired electrons and the porphyrin radical electron) is used as a criterion for comparison between synthetic porphyrins and heme-proteins.

In this study, two tetraarylporphyrins with highly electron-withdrawing substituents on the *meso*-phenyls are synthesized, and a new method for work-up of 5-(2, 6-dinitrophenyl)-10, 15, 20-tris-(2, 6-dichlorophenyl)porphyrin (TDCPDNPP) is reported. A method reported herein provides a significant increase in yields for porphyrins with *meso*-substituted *o*-dinitrophenyls.

The oxoferryl TDCPDNPP porphyrin π -cation radical is compared to the oxoferryl tetramesitylporphyrin π -cation radical (TMP). Because the oxoferryl TDCPDNPP π -cation radical has highly electron-withdrawing nitro-groups and different molecular orbital symmetry than the TMP, its spin-spin coupling was expected to be weakened, but remains strongly ferromagnetic. These results would support evidence that substitutions on the *meso*-phenyls do not cause a significant enough perturbation in unpaired spin density on the porphyrin macrocycle to change spin-spin coupling.

Acknowledgments

The research presented in this technical report was made possible in part by a United States Public Health traineeship and by the National Institute of Health. Also, a special thank you to my advisor, Dr. Avram Gold, and Dr. Karupiah Jayaraj for their assistance during research and to Dr. Louise M. Ball and Dr. Cindy Schauer.

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Introduction

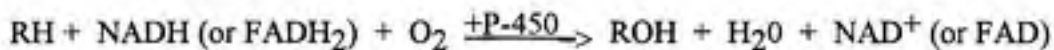
Oxidases, Oxygenases and Peroxidases

In recent years, there has been an increasing amount of research carried out on what are considered environmentally relevant enzymes. Of particular interest are those enzymes which interact with molecular oxygen directly to catalyze redox reactions. Enzymes that add one or both of the atoms of dioxygen to a substrate are known as oxygenases[19]. Those enzymes which require donation of two electrons and two protons to transfer one atom of molecular oxygen to a substrate while reducing the second atom of molecular oxygen to water are known as monooxygenases, while those that incorporate both atoms of molecular oxygen are dioxygenases. Oxidases oxidize a substrate without incorporation of oxygen into the substrate. Peroxidases act through the same putative transient as oxygenases, but use hydrogen peroxide as a source of both oxygen and electrons to oxidize a substrate[19].

Of particular interest to this project is the class of enzymes known as cytochromes P-450. Cytochromes P-450 (also known as mixed function oxygenases, MFOs, or P-450) are a group of monooxygenases that catalyze a large number of redox reactions and that derive their name from their unusually red-shifted Soret band in the uv-visible spectrum when the reduced (ferrous) enzyme is coordinated to carbon monoxide[19,20]. Although the oxidases and peroxidases, including chloroperoxidase, are environmentally important, the major discussion will be on cytochrome P-450 with a few comparisons to other systems where relevant.

Cytochrome P-450 enzymes are ubiquitous to all eukaryotes and many prokaryotes. In single-cell organisms, these enzymes detoxify and/or breakdown metabolites that are naturally produced in cells during respiration and oxidize non-polar,

hydrophobic molecules caught inside the cell membrane with the aid of oxygen and electron carriers such as NADH and FADH₂[7].

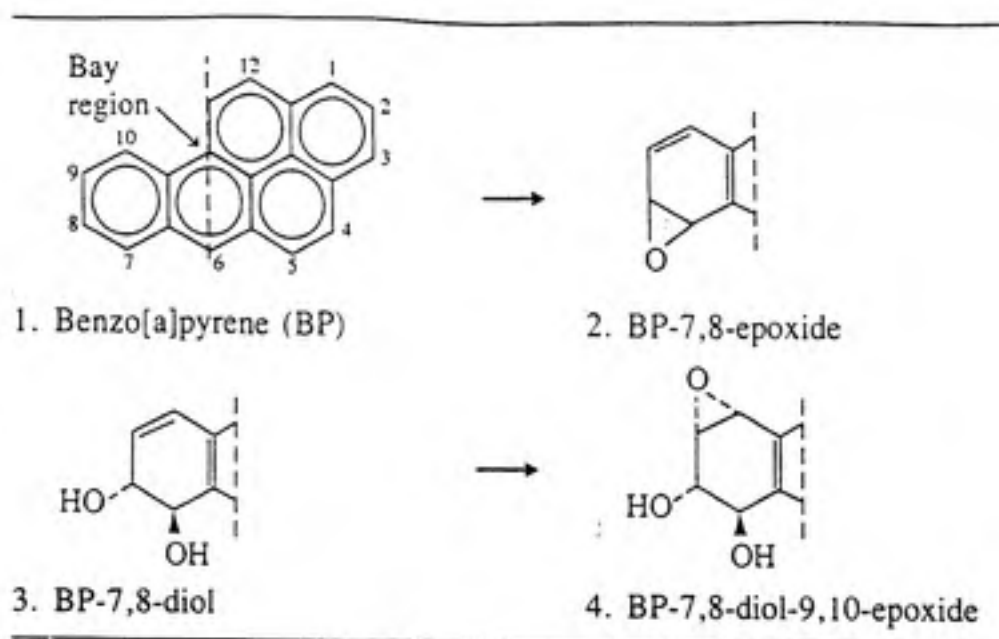


(Adapted from ref. [7], p. 738)

In addition to cellular functions, P-450 enzymes also function in larger organisms by regulating levels of hormones, metabolizing cholesterol, converting cholesterol to steroidal hormones, and acting as a systemic detoxification pathway by hydroxylating non-polar compounds to produce more polar derivatives which may be more readily excretable and less reactive. In addition to the above hydroxylation reaction, cytochrome P-450 also catalyzes a variety of other reactions, such as epoxidation reactions, heteroatom dealkylations(N-, S-, and O-), N-oxidations, sulfoxidations, and dehalogenations[19]. Hydroxylation, epoxidation, and dealkylation pathways are particularly important in detoxifying foreign substances, or xenobiotics, which may enter the cell.

For the majority of substrates, these reactions detoxify natural metabolites of cellular respiration and xenobiotics or reduce their reactivity with biomolecules, but metabolites of certain classes of compounds have proven more reactive and/or toxic upon oxidation by P-450s. One well-known group of compounds that may be activated upon oxidation by P-450 is polycyclic aromatic hydrocarbons, or PAHs. These lipophilic compounds are relatively non-reactive before they are oxidized by P-450s, however, some metabolites produced from these PAHs by P-450s are highly reactive and form adducts with critical cellular macromolecules. Formation of a covalent bond between the PAH metabolite and a DNA base, and failure of DNA repair enzymes to recognize and correct the adduct may initiate the process of carcinogenesis. An example of the

activation of the PAH benzo[a]pyrene by P-450, is shown below. (Adapted from ref.[9], p.174.)



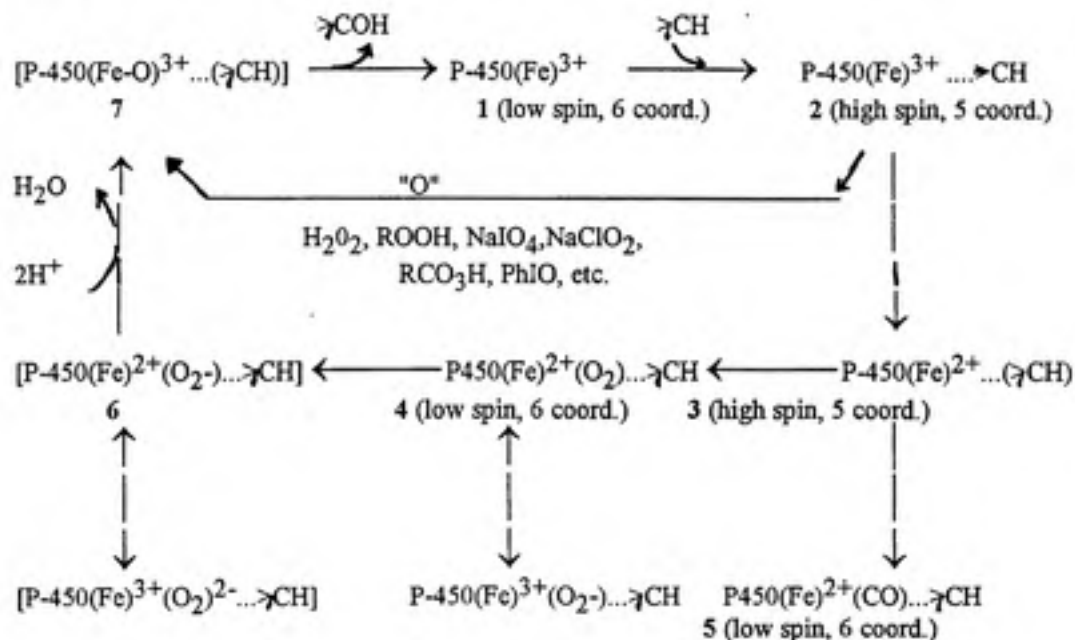
*(Note that arene epoxides are detoxified quickly by epoxide hydrolase[9] or conjugated to form an easily excretable compound. The 7,8-diol-9,10-epoxide is not a good substrate for epoxide hydrolase and has been shown to be the species forming the majority of adducts of benzo[a]pyrene. Hence the diol epoxide is considered the ultimate carcinogen[9, 19].)

Because P-450-mediated activation of environmental contaminants affects both humans and other species, research has been directed towards determination of how P450 enzymes function. In particular, researchers are interested in the reaction pathway of cytochromes P450, because relatively little is known about the catalytically active species of this highly versatile enzyme. It is postulated that a better understanding of the reaction mechanism of P-450 may allow selective inhibition of activation pathways of

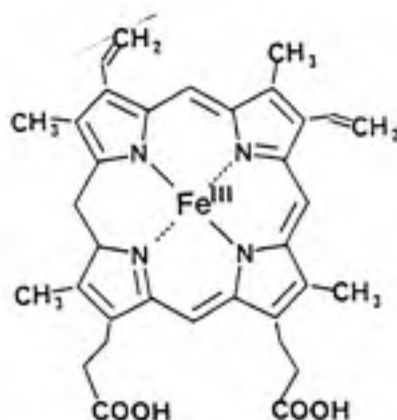
P450[19]. In addition, it is possible that better understanding of these enzymes may lead to the development of a genetically or synthetically engineered enzyme which may be used for bioremediation in the future.

A commonly accepted pathway for activation by P450 is shown below[19]. However compound I, the oxoferryl porphyrin π -cation radical, which is the putative intermediate, is so short-lived that researchers have not yet been able to observe it and conclusively show that P450 does indeed proceed through this transient. Compound I has been effectively studied in chloroperoxidase and horseradish peroxidase[18-20], and is proposed as the active species for P450 because these enzymes all can perform similar chemistry.

P450 PATHWAY (adapted from ref. 19):



Because the peroxidases, chloroperoxidase and P-450s demonstrate similarities in function and are presumed to have similar active site chemistry, much of the information that is derived from the study of one of these classes of proteins is applied to the other classes of proteins. However, it is important to note that although these enzymes all are thought to contain iron-protoporphyrin IX at the active site, each has distinct capabilities, as a result of differences in the structural configurations of the amino acids surrounding the prosthetic group.

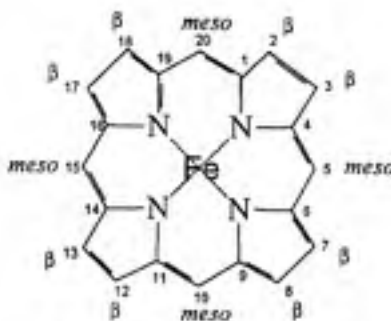


Protoporphyrin IX

Because investigators have failed to observe the compound I transient of cytochrome P450 enzymes, another approach has been taken to elucidate the reactivity and electronic features of P450s. Biomimetic model compounds have been synthesized using the iron porphyrin prosthetic group. Although research on P450s has continued, iron porphyrins have offered a structural simplicity that is easier to manipulate and gives clearer results than studying the proteins themselves. Synthesis of iron porphyrins allows additions of substituents to both *meso*- and pyrrole β -carbon positions. In addition, iron porphyrins may be synthesized on a large scale. Studies involving P450 proteins must be done on a much smaller scale and do not allow the structural perturbations afforded by the synthetic iron porphyrins.

Although extracted prosthetic groups or synthetic models of active sites do not always behave similarly to the native enzyme, early work with iron porphyrins showed promise, as certain iron porphyrins were shown to catalyze hydroxylation and epoxidation reactions[10]. Other iron porphyrins were thought to have electronic structures similar to P450[11] or peroxidases[11,12].

Attempts have been made to study the iron-protoporphyrin IX system itself; however, studies of the high valent complex are ambiguous at best, because the protoporphyrin IX system undergoes auto-oxidation at the *meso*-position. Therefore, porphyrins have been synthesized that are protected from auto-oxidation.



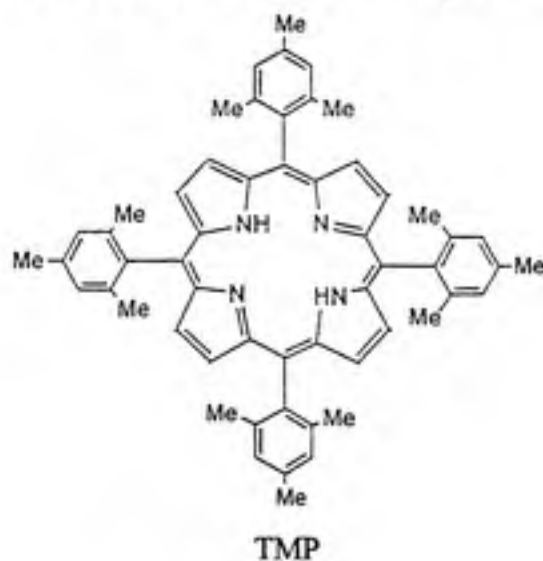
General Numbering Scheme for Porphyrins

TMP as the First Well Characterized Model

The first well characterized high-valent iron porphyrin model complex was the oxoferryl tetramesitylporphyrin π -cation radical $[\text{Fe}^{\text{IV}}=\text{O}(\text{TMP})\cdot^+]$ [12, 13]. Although many model compounds catalyze reactions similar to those catalyzed by heme-enzymes, it was this model, $[\text{Fe}^{\text{IV}}=\text{O}(\text{TMP})\cdot^+]$, that permitted definitive study of the oxoferryl porphyrin π -cation radical electronic structure. Therefore, TMP is often used as a reference to which new model compounds are compared, because it has been so well studied.

Some differences between model compounds and heme-enzymes[8,13] have been observed. Investigators are still trying to describe the spin-spin coupling between the

S=1 ferryl iron and the porphyrin π -cation radicals in both enzymes and synthetic analogs. In horseradish peroxidase-compound I (HRP-I) and chloroperoxidase compound I (CPO-I), coupling between the iron(IV)-oxo and the porphyrin π -cation radical electrons is considered weakly ferromagnetic[14,15] and anti-ferromagnetic[8,16], respectively. The model derivatives synthesized to-date, by contrast, show only strong ferromagnetic coupling[8,13]. Work with synthetic high valent iron porphyrins has been undertaken to examine the possibility that addition of electron-withdrawing or releasing groups to different regions of the porphyrin ring would change the electronic structure of these porphyrins so that either ferromagnetic or anti-ferromagnetic coupling could be favored. Knowing more about the properties that affect the coupling between the oxoferryl group and the porphyrin π -cation radical from studies of model compounds, along with knowledge of the effects of axial ligands[18-20] could possibly give greater insight into mechanisms of protein catalysis and why proteins with very similar reactive sites have such different reaction capabilities.

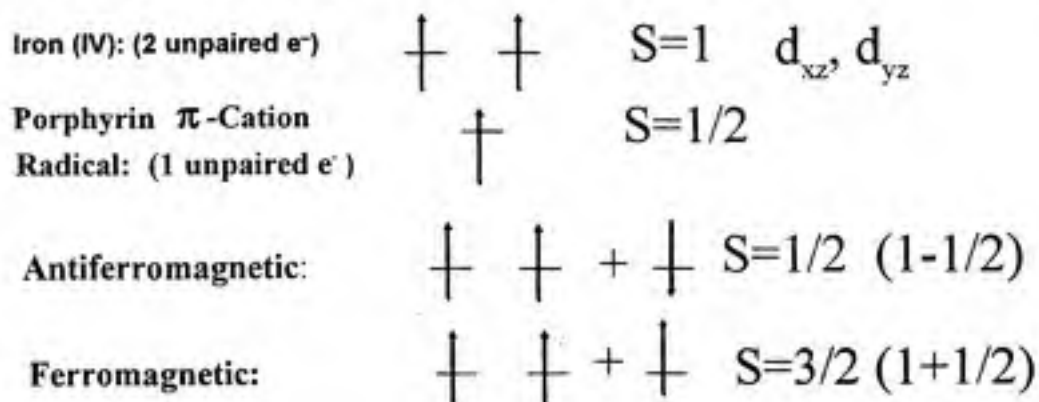


Spin Coupling and Symmetry

In the compound I analog of FeTMP, Fe(IV) is in an S=1 spin state, with one unpaired electron in each of the d_{xz} , d_{yz} atomic orbitals. The oxidized porphyrin ligand

contains one unpaired electron with spin $S=1/2$. The porphyrin ligand affects the electronic structure of the central metal, and it follows that the unpaired electron of the porphyrin could interact with the unpaired iron electrons so the whole molecule will have combined spin state. However, quantitative description of the influence of the unpaired porphyrin electron on the unpaired iron electrons is not simple, and requires knowledge of the singly occupied porphyrin orbital symmetry as well as the orbital coefficients.

There are three ways in which the porphyrin radical electron and the iron unpaired electrons can interact or couple. First, the electrons can align with their spins in a parallel manner. When the two spin systems align in a parallel manner (ferromagnetic coupling), the total system has a net spin $S=3/2$ ($\text{Fe(IV)} S=1 + \text{porphyrin } S=1/2$). In the second case, the electrons align with their spins in an antiparallel manner giving a net spin $S=1/2$ ($1-1/2$) and coupling may be referred to as anti-ferromagnetic. Finally, in the third case, the two spin systems do not interact or interact so weakly that the spins cannot be considered as a combined system. In this case, the two spin systems remain separate and can be thought of as infinitely far apart.



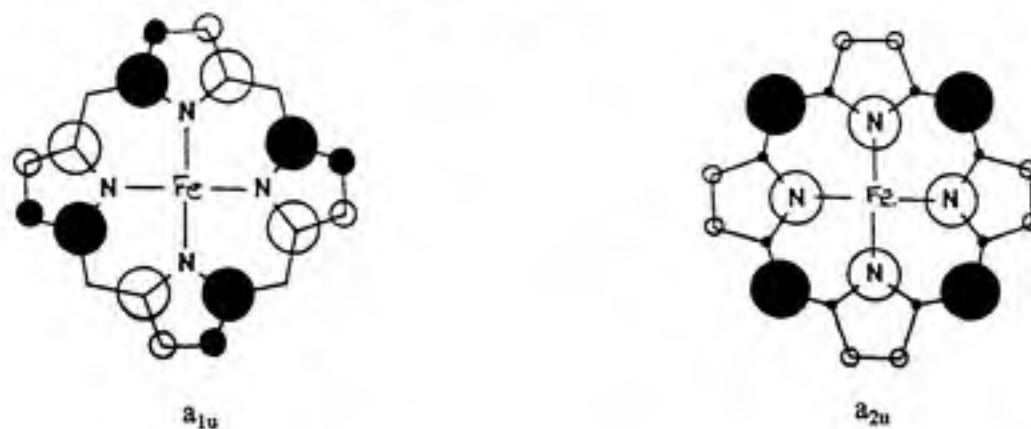
Two Types of Spin-Spin Coupling

The symmetry of molecular orbitals theoretically influences which type of interaction occurs. The only allowed interactions between the iron d-orbitals and the highest occupied molecular orbitals (HOMOs) of the porphyrin are those interactions

between orbitals of the same symmetry groups[28]. An examination of the symmetries of the porphyrin molecular orbitals and the iron atomic orbitals shows whether interactions between unpaired electrons of iron and porphyrin HOMOs are symmetry allowed.

The simplest case to envision is an iron ion in an octahedral ligand field. The iron d-orbitals transform as e_g and t_{2g} [28]. Once a porphyrin is complexed with iron, the symmetry of the molecule changes, and therefore the iron orbital transformations do as well. In the highest symmetry D_{4h} case, the iron d-orbitals transform as e_g ($d_{yz,xz}$), a_{1g} (d_{z^2}), b_{1g} ($d_{x^2-y^2}$) and b_{2g} (d_{xy}). Gouterman, *et al.* have performed extensive calculations necessary to determine MOs for the D_{4h} case[30,31]. When substituents are added to the porphyrin macrocycle, the symmetry may be further lowered from D_{4h} . Even though the symmetry group to which the molecule belongs changes as well as the irreducible representations of the MOs, extrapolating from the highest symmetry for porphyrins to less symmetric groups is possible. However, since only the D_{4h} case has been formally calculated, authors often refer to orbitals of porphyrins with lower symmetry as if they belonged to the D_{4h} case, using the labels a_{1u} and a_{2u} to describe the two nearly degenerate porphyrin HOMOs.

In the D_{4h} porphyrin π -cation radical case, either the a_{1u} or a_{2u} molecular orbital is half occupied and could possibly interact with the iron electrons. The a_{1u} and a_{2u} MOs are shown below (adapted from ref.[42]):



However, in D_{4h} symmetry neither a_{1u} nor a_{2u} is allowed by symmetry to mix with either of the half-filled d-orbitals of the ferryl iron that transform as e_g , and coupling will always be ferromagnetic. Spin-spin coupling, however, is postulated to be smaller for a_{1u} than for a_{2u} porphyrin π -cation radicals, since a_{1u} has nodes at the pyrrole nitrogens[8]. If the porphyrin symmetry is reduced to C_s , then mixing of both porphyrin HOMOs and the singly occupied iron d-orbitals is allowed and, coupling could be antiferromagnetic. However, in addition to being symmetry allowed, interaction between the iron d-orbitals and the porphyrin HOMO must be energetically favorable. Therefore, even in porphyrin radicals with C_s symmetry, in which antiferromagnetic coupling is allowed by symmetry, the observed coupling may be ferromagnetic.

In the study of the electronic structure and coupling of heme-enzymes, porphyrins with pyrrole β -substituents (e.g. protohemes) have been primarily a_{1u} in character. Although the most relevant porphyrin to study with regard to coupling in heme-enzymes is the iron-protoporphyrin IX system, it is not resistant to auto-oxidation when the high valent complex is generated. Therefore, phenyl groups at the meso positions have generally been used to protect against auto-oxidation. These *meso*-tetraarylporphyrin π -cation radicals have been typically a_{2u} in character, but it was hoped that, with substitution of strongly electron-withdrawing substituents on the phenyls, the a_{2u} could be lowered in energy, possibly causing an inversion in the ordering of the two HOMOs and favoring electron abstraction from the a_{1u} molecular orbital[45]. In this manner, it was hoped that the coupling could be varied without the danger of auto-oxidation. It was also hoped that by lowering symmetry through *meso*-substitution with different aryl groups, orbital mixing would increase the antiferromagnetic contribution to spin coupling.

To date, no high-valent model compounds have been synthesized that have antiferromagnetic coupling[21-27]. It was hoped that the oxoferryl 5-(2, 6-dinitrophenyl)-

10, 15, 20-tris(2, 6-dichlorophenyl)-porphyrin π -cation radical, or $[\text{Fe(IV)=O(TDCPDNPP)}]^+$, with its electron withdrawing nitro groups, would be even closer in energy to the a_{1u} , as discussed above, and therefore be more weakly coupled than previously studied porphyrins. In addition, the oxoferryl π -cation radical of this complex has C_s symmetry and the possibility of antiferromagnetic coupling. Since the 5, 10, 15, 20-tetrakis(2,6-dichlorophenyl)porphyrin, or TDCPP, and 5-(2-chloro-6-nitrophenyl)-10, 15, 20-tris(2, 6-dichlorophenyl)-porphyrin, or TDCPMNPP, had been studied and reported, the results from the dinitro-phenyl derivative could be studied in a series to determine the effect on the porphyrin ring electron densities by increasing the electron-withdrawing substituents on the meso-phenyls.*

Porphyrins as Catalysts

In addition to using porphyrins to study electronic structure, scientists have made efforts to utilize the reaction capabilities of porphyrins. In particular, halogenated porphyrins have demonstrated efficient catalytic capabilities[33-40]. Fully halogenated (perhalogenated) tetraphenylporphyrins have been studied recently with the idea that the resulting catalyst would be highly resistant to auto-oxidation and enhanced with respect to the metal-oxo reactivity. It was thought that the halogen-substituents would tend to draw the electrons to the periphery of the macrocycle, destabilizing the metal-oxo species, thereby increasing reactivity. Recent studies have shown that perhalogenated porphyrins are more efficient catalysts than the partially or non-halogenated porphyrins for a large number of oxidations[34-36,39,40]. For example, perhalogenated porphyrins have been shown to oxidize linear alkanes under mild conditions[40].

* Note that, recently, a predominantly a_{1u} porphyrin was synthesized that is protected against auto-oxidation without meso-phenyls[32].

Molecular structure studies were performed in order to understand why these perhalogenated porphyrins are more effective oxidation catalysts than the β -halogenated tetraphenyl or tetramesityl species[37,38]. These studies showed severe saddle-shaped distortions occur for all the fully β -brominated tetraarylporphyrins. This saddle-shape, coupled with the electron-deficiency of the perhalogenated complexes, was proposed to explain the efficiency as oxidation catalysts[38]. Work was undertaken on a β -chlorinated tetrakis(pentafluorophenyl) porphyrin to determine the effects of electronegativity and macrocycle distortion in a series of porphyrins with more electronegative halogen substituents and to develop an understanding of the mechanisms of catalysis by the β -halogenated porphyrins. One objective of studies undertaken on high-valent transients generated from Fe- 2,3,7,8,12,13,17,18-octachloro-5,10,15,20-tetrakis(pentafluorophenyl)porphyrin was to derive mechanistic inferences from effects of molecular and electronic structure on the formation of compound I. It has been debated whether the perhalogenated porphyrins can stabilize the two oxidizing equivalents above resting state required to form the oxoferryl porphyrin π -cation radical, or whether reactions involving perhalogenated porphyrins go through the (porphyrin)Fe(IV)=O species, which is only one oxidizing equivalent above resting state. This suggestion is explained on the basis that the already electron-deficient porphyrin ring is not oxidized to generate the porphyrin π -cation radical, while the iron-oxygen bond is highly destabilized by the electronegative porphyrin. A goal of this project was to determine whether the β -chlorinated porphyrin could form the oxoferryl porphyrin π -cation radical. The project was also designed to study the Fe(IV)=O species.

Spectroscopic Techniques- An Overview

EPR and Mössbauer Spectroscopy

EPR and Mössbauer techniques are used in porphyrin studies to determine whether successful generation of the high valent species has occurred and to learn more

about the coupling between the oxoferryl $S = 1$ system and the porphyrin cation radical. Mössbauer uses the radioactive decay of a moving ^{57}Co source to excite ^{57}Fe from $I = 1/2$ to $I = 3/2$ nuclear spin state, and to measure resonant absorption of irradiation as a means of observing perturbations caused at the iron nucleus by the surrounding environment. By convention, the absorption characteristics are compared to iron in metallic iron foil. Because of the experimental set-up, the two parameters of interest are measured in terms of velocity shifts (mm^{-1}): isomer shift (δ), which is characteristic of valence, and quadrupole splitting (Δeq), a measure of electric field gradient (i.e., asymmetry). Unpaired electrons on ligands of iron, such as the π -cation radical, will cause additional perturbation of the Mössbauer spectrum.

Oxidation State of Iron	Range of Isomer Shifts
Fe(II)--low spin	+0.9 - +1.2 mm/s
Fe(III)-high spin	+0.15 - +0.7 mm/s
Fe(IV)	0.0 - +0.3 mm/s
Fe(VI)	~-1.2 mm/s

The resting state for the iron porphyrins and the heme proteins mentioned above is the ferric form. Using the Mössbauer technique, it is possible to distinguish between high and low spin ferric heme-enzymes. Mössbauer spectroscopy has been important in the work to identify axial ligands[20], as it is generally considered that cysteine or cysteinyl ligands favor high spin Fe(III) while histidine ligands generally favor low spin Fe(III).

In addition, Mössbauer spectroscopy also shows with some certainty that the oxoferryl species has been generated in oxidation reactions. Mössbauer spectroscopy is useful for determining general environmental differences about the iron center and confirms the presence of a porphyrin π -cation radical (by hyperfine splitting); however data provide little additional detail about the porphyrin π -cation radical electronic structure.

Electron Paramagnetic Resonance (EPR) is often used in studies investigating the coupling in iron-porphyrins and in heme-enzymes with half-integral net spins. EPR uses the microwave energy in the presence of an applied magnetic field to cause transitions between electron spin states. In the presence of an applied field, an unpaired electron can align with the field ($m_s = -1/2$) or opposed to the field ($m_s = 1/2$). These two spin states are degenerate in the absence of an applied field, but in the presence of the field, the energy that separates the two states can be described by the following equation:

$$\Delta E = h\nu = g\beta B_0$$

where h = Planck's constant

ν = microwave frequency of the excitation energy

g = Lande's splitting factor ("g" factor)

β = Bohr magneton

B_0 = strength of the applied magnetic field.

The g factor may be anisotropic, with differing x , y , and z components. For molecules with axial symmetry $g_x = g_y \neq g_z$. In the cases of axially symmetric porphyrins, the coordinate system is defined so that g values are reported as g_{\parallel} ($= g_z$) and g_{\perp} ($= g_x, g_y$).^{*} The fields at which the g_{\parallel} and g_{\perp} transitions are observed allow the nature of coupling (ferromagnetic or antiferromagnetic) between the unpaired electron on the porphyrin ring and the unpaired iron spins to be determined. Ferromagnetic coupling of the ferryl iron with the porphyrin radical produces signals at $g^{\text{eff}} \sim 2(g_{\parallel})$ and $4(g_{\perp})$ [13], while antiferromagnetic coupling results in a signal with values of $g^{\text{eff}} \sim 2(g_{\parallel} \text{ and } g_{\perp})$ [45]. Weak- or no-interaction between spins results in a broad, low-intensity signal, that is not very well defined.

^{*} (Usually, the first derivative of the data is reported. Therefore, this report will only describe data in this form.)

Resonance Raman Spectroscopy:

Resonance Raman spectroscopy uses laser light at a frequency near an electronic absorbance band (e.g. the Soret band of porphyrins) for simultaneous electronic and vibronic excitation of a molecule in order to observe vibrational frequencies. Certain vibrational frequencies have been correlated with specific vibrational modes characteristic of the porphyrin skeleton. Important marker bands are ν_2 , ν_4 , ν_{11} and the Fe=O stretch, which have been shown to be sensitive to changes in porphyrin structure. In particular, the shift of ν_2 on oxidation of the porphyrin to a π -cation radical is used to identify whether the symmetry state of the singly occupied molecular orbital is a_{1u} or a_{2u} . This symmetry correlation is explained by the fact that the ν_2 band is composed primarily of a pyrrole β - β carbon stretch. Since the porphyrin a_{1u} molecular orbital has nodes between the pyrrole β -carbons, abstraction of an electron from the a_{1u} molecular orbital relieves an antibonding interaction, in effect strengthening the bond and resulting in a shift of ν_2 to higher frequency. Conversely, removal of an electron from the a_{2u} molecular orbital decreases a bonding interaction and results in a shift of ν_2 to lower frequency. While spin coupling has not been shown to correlate with the symmetry of the singly occupied porphyrin π -cation radical MO, resonance Raman spectroscopy does provide greater insight into both electronic and molecular structure of the porphyrins by correlation of skeletal modes with various physical-chemical descriptors.

Experimental Section

Synthesis of 5-(2,6-dinitrophenyl)-10,15,20-(2,6-dichlorophenyl)porphyrin free base (TDCPDNPPH₂). (See Scheme 1.) The method of synthesis for TDCPDNPPH₂ followed the published Lewis acid catalyzed condensation of aryl aldehydes[46], with a ratio of 3:1 2,6-dichlorobenzaldehyde: 2,6-dinitrobenzaldehyde. Methylene chloride (1.6 L, dry), ethanol (3.2 mL), 2,6-dichlorobenzaldehyde (2.5 g), 2,6-dinitrobenzaldehyde(1.0 g) were placed in a 3 L, three-necked round bottomed flask (with CaSO₄ drying tube) and degassed with argon three times. Freshly distilled pyrrole (1.01 g) and BF₃·Et₂O catalyst (1 mL) were added to the mixture by syringe, and the solution was stirred under argon at room temperature overnight. Oxidation of the initially formed porphyrinogen to porphyrin was accomplished by addition of *p*-chloranil (approximately 3 g) and refluxing for 2-3 hrs exposed to dry air.

Although the Lewis acid condensation with 2,6-dinitrobenzaldehyde has been documented as low yield with difficulties in purification[27, 29], a new method for purification was developed based on the method used by Shelnut[44]. Through this method, yields as high as 40-50 mg (3-4 %) of TDCPDNPPH₂ were obtained. (Note that best yields reported for any porphyrin are ~30 %.) Due to solubility problems, the free base can be easily lost to column during cleanup, in addition, any remaining *p*-chloranil or quinone seems to complicate purification and is not readily separable from the free base using column chromatography with chlorinated solvents or toluene. Purification of the free base and complete separation from the quinone was only possible when the original solution from the Lewis acid-catalysis reaction was evaporated to dryness over 300-500 g of alumina which had been washed with methanol. The alumina was then

washed with methanol until the solution was colorless. [Note that Shelnett, *et al.*, state to wash until no uv-vis detectable material comes off. However, the solubility of the free base in large quantities of methanol was unknown, and it was thought that over-washing of a small amount of product might result in additional loss of porphyrin.] Next, the alumina was washed with methylene chloride until no detectable Soret band was present in the eluent and this solution was evaporated to dryness over 300-500 g of silica gel. This was again extracted with methylene chloride until the uv-vis showed no Soret. [Note that the solution remains colored.]

Unlike the Shelnett, *et al.*, method, the rest of the chromatography was done using silica gel. A primary column was run on a 8 cm x 60 cm silica gel column with methylene chloride eluant. Although the TDCPPH₂ is first to elute, at this stage, both porphyrins co-elute with several side-products. Subsequent columns were run with chloroform, as TLC plates suggested that separation of the two porphyrins is greater in chloroform than in methylene chloride, however, the TDCPDNPPH₂ is less soluble in chloroform than in methylene chloride and, thus, loss occurred on the column. In addition, there was a substantial amount of tailing from TDCPPH₂ in chloroform such that even the relatively well separated TDCPDNPPH₂ band was approximately a 1:1 mixture of the two porphyrins. An important improvement was achieved by first separating the porphyrin mixture from the side-products, and then sequentially reducing the amount of TDCPPH₂ present by removing approximately 50 mL aliquots of pure TDCPPH₂ from the head of the band on each column. Later, it was discovered that by using a 1:1 mixture of chloroform to methylene chloride, better separation was achieved without compromising solubility of the TDCPDNPPH₂. In this mixture, there is substantial tailing of the TDCPDNPPH₂, but it is generally free of TDCPPH₂. As the proportion of TDCPPH₂ in the mixture decreases, TDCPDNPPH₂ may be purified with pure chloroform. (Note that at all but the purest stages, it is easy to overload the columns and lose the TDCPDNPPH₂ as precipitate on the column. Recovery by extraction is

difficult even with 5% methanol. Also, note that the solubility and behavior of relatively pure TDCPDNPPH₂ is significantly different from the unpurified free base.) The free base was further purified by TLC and checked by NMR for purity before metallation: (500MHz, CDC₁₃), 8.62 ppm (bs, 6 H, pyrrole-H), 8.58 ppm (d, 2 H, pyrrole-H), 8.5 ppm (d, 2 H, *m*-H nitrated phenyl), 8.17 ppm (t, 1 H, *p*-H nitrated phenyl), 7.78 ppm (d, 8 H, *m*-H chloro phenyls), and 7.70 ppm (t, 3 H, *p*-H chloro phenyls).

Fe Metallation of TDCPDNPPH₂. Free base (400 mg), pure by NMR, was dissolved in 100 mL dry DMF; 40 mg FeCl₂ was added and the solution was refluxed at 180°C for 1 hour under argon with a drying tube. After one hour, an additional 100 mg FeCl₂ was added and the solution was refluxed for 10 min more, then opened to air and refluxed one hour more. The heat was then removed, and the solution was left stirring over night. Purification was achieved by using a silica gel column eluted with chloroform to remove any remaining free base. The iron porphyrin complex eluted only when the solvent was changed to 5% methanol in chloroform. Further purification was achieved by using a silica gel TLC plate and chloroform. (This method yielded 398 mg (94 %) of the iron complex.) Note: Pre-eluting the blank TLC plate with chloroform was necessary both to decrease the precipitate that formed and to remove any ubiquitous organic molecules present which might fluoresce during resonance Raman experiments.

⁵⁷Fe Metallation of TDCPDNPPH₂. ⁵⁷Fe metallation was achieved by refluxing 1.0 mg Fe foil in 7.5 mL HCl and 7.5 mL methanol under argon until the ⁵⁷Fe dissolved. Then, the solvent was removed by bulb to bulb distillation and replaced with 10 mL DMF and 10 mL dry collidine containing the porphyrin. This new solution was refluxed at 170°C for approximately four hours under argon, and the solvent was again removed by bulb to bulb distillation. (An approximately 1:1 molar equivalent of ⁵⁷Fe to porphyrin was used in each reaction.) Separation of the coordinated porphyrin from the free base was

performed using a short silica gel column with chloroform eluant, as the free base moves much faster than the complexed porphyrin. Note that there may be two bands or one large diffuse band for the metallated complex, as the chloride counter ion easily metathesizes with hydroxide on silica. This mixture can be easily converted back to FePCl by bubbling HCl through the solution after purification is complete. It is important to convert all of the material to FePCl before beginning the exchange with the triflate, because the hydroxo complex does not exchange as cleanly with the triflate as does the chloro complex.

Triflate. In a dry box, FePCl (or $^{57}\text{FePCl}$) was dissolved in a minimum amount of freshly distilled THF and transferred to a Schlenk tube. One mole-equivalent of silver triflate was dissolved in THF and added to the FePCl solution for a total volume of 25 mL. The solution was refluxed under argon for 2-1/2 hours until the uv-vis showed no signs of starting chloro species. THF was removed by bulb to bulb distillation and after addition of methylene chloride, the reaction solution was filtered through a medium glass frit in the dry box to remove the silver chloride precipitate. The filtrate was evaporated and the remaining triflate complex was stored under argon. No further purification was necessary.

Low Temperature Oxidation with mCPBA (General Procedure). Stock solutions of 4.8 mg mCPBA in 0.31 mL methanol- d_4 and 2.3 mg FePTf in 2 mL dry methylene chloride were made. 0.6 mL of the FePTf solution was cooled to -80°C in a uv-visible spectroscopy reaction vessel and 0.1 mL of the mCPBA solution was added slowly so as not to raise the temperature and air was bubbled into the reaction vessel to stir the solution. The high valent complex of FeTDCPDNPPTf was stable for 1-1/2 hours and the iron(IV) complex can be formed by adding an equivalent of 1-methyl-imidazole in

dry methylene chloride after the mCPBA solution is added. This complex seems stable at least over night. (See Scheme 3.)

Fully Halogenated Species:

Tetrakis(pentafluorophenyl) octachloroporphyrin free base (TPFPCl₈PH₂) was synthesized by first synthesizing tetrakis(pentafluorophenyl)porphyrin free base[45], complexing it with zinc, and then chlorinating with N-chlorosuccinimide to fully chlorinate the pyrrole β -carbon positions on the porphyrin. (See Scheme 2.)

Synthesis of Tetrakis(pentafluorophenyl)porphyrin free base (TPFPPH₂). The method of synthesis for TPFPPH₂ followed the published Lewis acid catalyzed condensation of pyrrole with aryl aldehydes [46] using pentafluorobenzaldehyde. Initially the porphyrinogen was oxidized using tetrachloro-1,4-benzoquinone (*p*-chloranil) under reflux in chloroform. However, chlorins remained present until oxidation with 2,3-dichloro-5,6-dicyanoquinone (DDQ) in refluxing toluene, suggesting that strong oxidizing conditions are necessary to completely oxidize all species to the porphyrin. Purification was accomplished on silica with a 1:1 mixture of hexane: chloroform as eluant. Product purity was checked by thin layer chromatography, uv-vis, and ¹H-NMR before proceeding to Zn insertion.

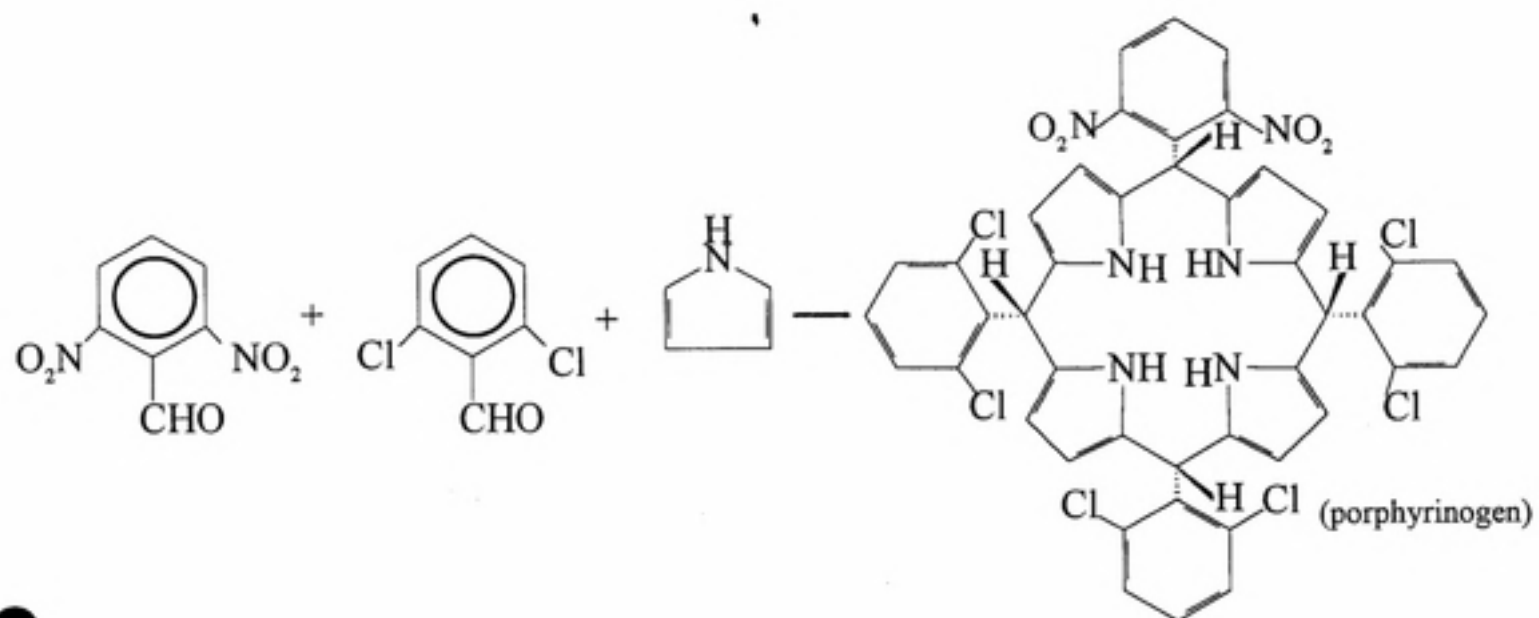
Zn Metallation of TPFPPH₂ (ZnTPFPP). The porphyrin (499 mg) was dissolved in 100 mL DMF and refluxed at 170°C. Zinc acetate was added to the refluxing mixture and reflux continued for 20 min. (Note that the brownish solution changed to purple immediately upon addition of ZnOAc.) The reaction was monitored by uv-vis until no free base remained. Product purity was checked by ¹H-NMR, uv-vis, and TLC. (Recovered 542 mg (99%) ZnTPFPP.)

NCS Chlorination of ZnTPFPP. In a typical procedure using a modified method from Gonzalves, *et al.*[5], 50 mg ZnTPFPP was dissolved in 100 mL chloroform and 2 g N-chlorosuccinimide (NCS) was added. The solution was refluxed for four hours with no change, then a 200 W tungsten lamp was added and the solution was allowed to reflux under irradiation for 24 hours. The reaction was terminated when there was no change in the uv-vis spectrum and TLC showed no starting material. The Soret of the fully chlorinated compound shifts to 443 nm from 427 nm for ZnTPFPP. At this point, ZnOAc was added to facilitate the purification process. The solution was then washed with 1M NaOH solution, water, then dried over sodium sulfate. The product was purified using 60:40 mixture of methylene chloride: hexane eluant on a silica gel column. Product purity was checked using TLC, uv-vis, ^{13}C -and ^{19}F -NMR. (If the chlorination was successful, there should be no ^1H -NMR signal.) Yields were ~100 mg (20%).

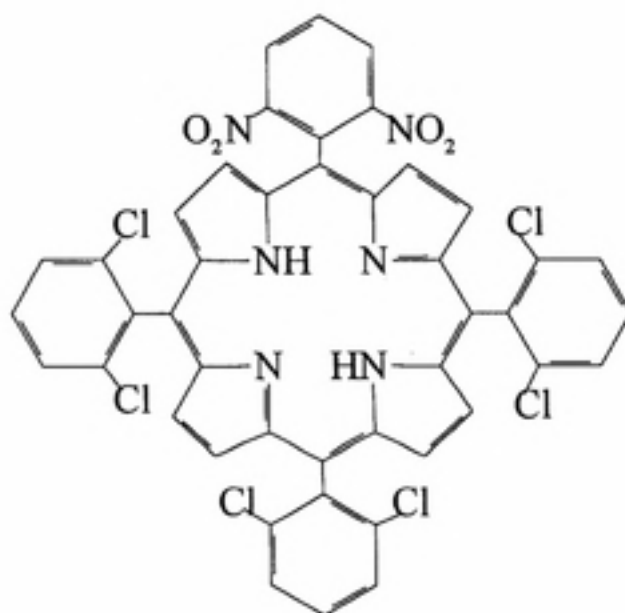
Zn Demetallation/Fe Metallation of ZnTPFPCl₃P. The free base was obtained by stirring the ZnTPFPCl₃P in 100 mL methylene chloride with 10 % trifluoroacetic acid for 24 hours. The solution was washed with water and with a saturated sodium carbonate solution, then dried over sodium sulfate. The free base was purified by chromatography on a silica gel column eluted with chloroform and the purity was confirmed by TLC and uv-vis. The free base was then dissolved in 30 mL DMF and refluxed with 100 mg FeCl₂ for three hours under argon. The solution was opened to air and refluxed further for one hour. Purification of the FeTPFPCl₃PCl was achieved on silica eluting first with 100 % methylene chloride to remove any remaining free base and then with 5 % MeOH in methylene chloride to elute the iron complex. A preparative TLC plate was run using chloroform eluant and no further purification was required after checking by mass spectrometry, ^{19}F -NMR, uv-vis, and analytical TLC.

Low Temperature Oxidation with mCPBA. Stock solutions of 4.8 mg mCPBA in 0.31 mL methanol-d₄ and 2.3 mg FePCl in 2 mL dry methylene chloride were made. 0.6 mL of the FePCl solution was cooled to -80°C and 0.1 mL of the mCPBA solution was added slowly so as not to raise the temperature and air was bubbled into the reaction flask to stir the solution. The FeTPFPCl₃PCl solution bleached immediately. Additional attempts with successively less concentrated mCPBA solution gave the same result. At this point, no complex remained for further attempts at oxidation.

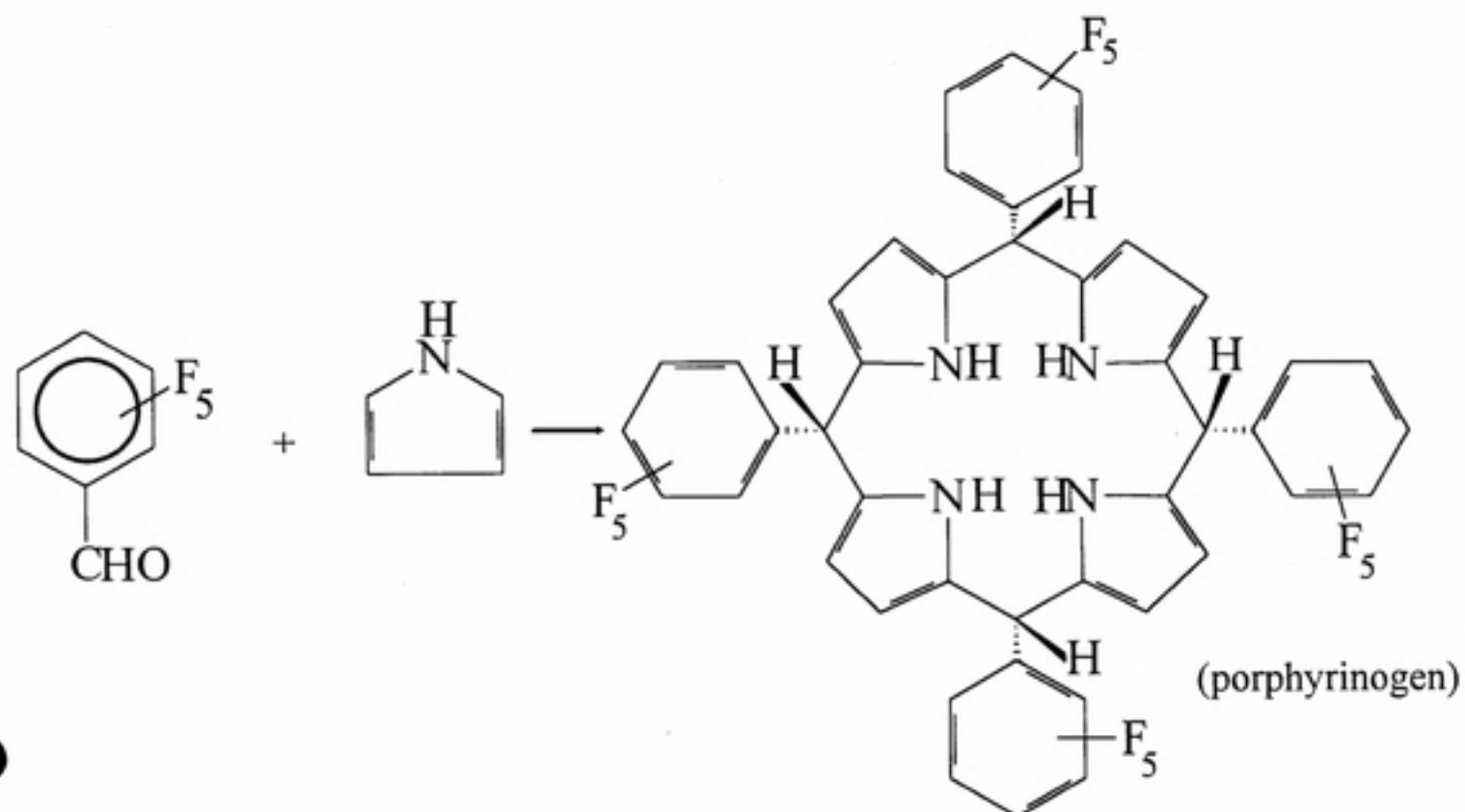
Scheme 1:



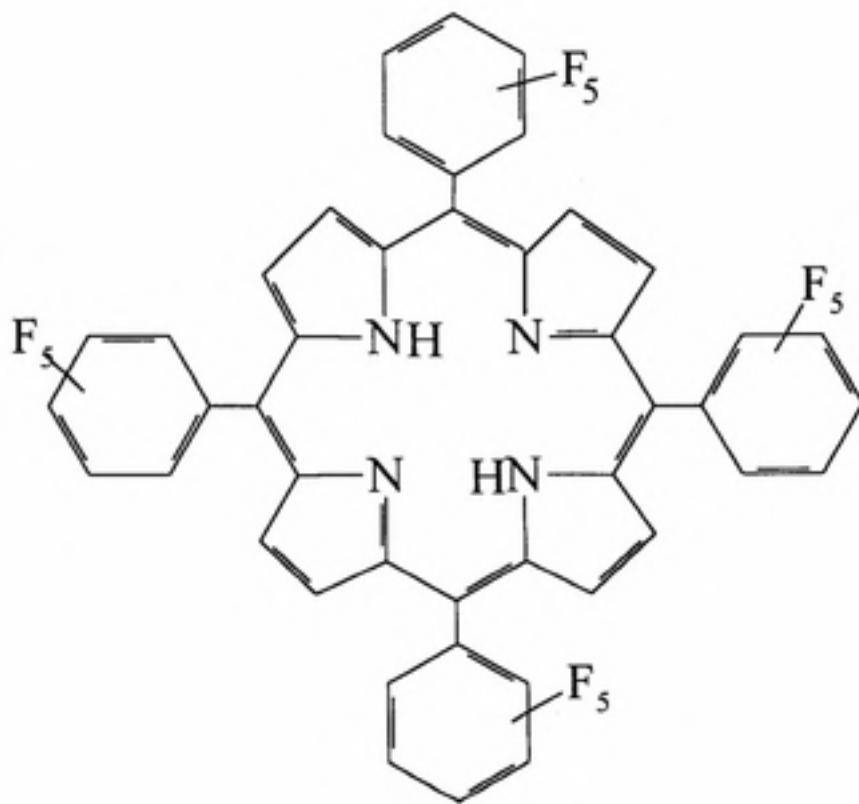
porphyrinogen

 $\xrightarrow{\Delta, p\text{-chloranil}}$ 

Scheme 2:

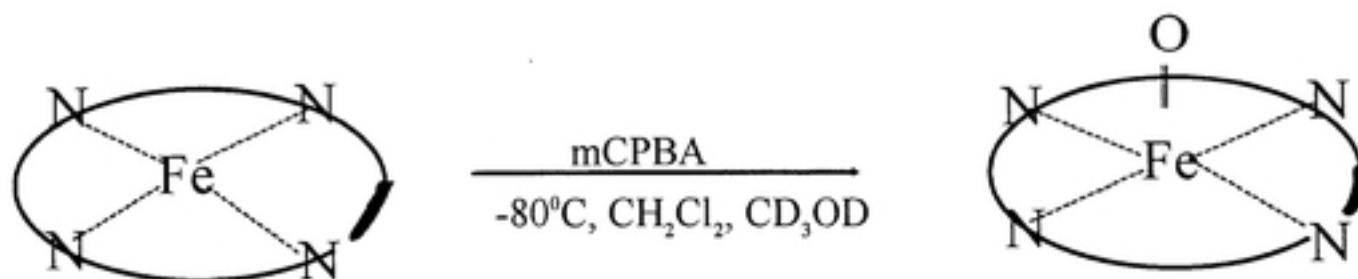


porphyrinogen

 $\xrightarrow{\Delta, p\text{-chloranil}}$ 

Scheme 3:

25



Note:



Results and Discussion

TDCPDNPP:

Initial attempts to make TDCPDNPP free base appeared unsuccessful as only TDCPP free base could be isolated. After several attempts, the dinitro-derivative was detected, but was not easily isolated. Since solubility of the purified porphyrin in chlorinated solvents was low, it was suspected that the desired dinitroporphyrin was indeed formed, but was not isolated using published procedures. Several months were spent developing a method by which to purify the dinitro-derivative. Finally, a modification of a method by Shelnut, *et al.* [44], was used and the porphyrin was purified. Although methodology is generally not reported in results and discussion, the difference between conventional methods and this new method merits mention. Before this method, only 5-10 mg of TDCPDNPP was collected out of a total yield of approximately 1 g of porphyrin per condensation. Because the quantity of TDCPDNPP collected was so small and resonance Raman is particularly sensitive to impurities, initial attempts at resonance Raman spectroscopy yielded weak and inconclusive spectra. However, employing the new work-up method, 40-50 mg yields of relatively pure TDCPDNPP were obtained. Only minimal cleanup was required for resonance Raman after the initial isolation. It is important to note that the apparent inability of previous investigators to isolate condensation products led to the conclusion that although the 2,6-dinitrobenzaldehyde was activated toward condensation, unfavorable steric factors prevented the condensation. Our results show that the condensation is not as sterically hindered as first believed.

Each reaction, including generation of the high-valent iron-porphyrin complex, was monitored by uv-vis spectroscopy. Spectra of the free base (Figure 1) show the

characteristic Soret band, though somewhat blue shifted at 419 nm ($\epsilon = 8.22 \times 10^4$), and the lower intensity three-peak pattern in the visible region at 512.2 nm ($\epsilon = 7.46 \times 10^3$), 589.5 nm ($\epsilon = 3.33 \times 10^3$), and 650 nm ($\epsilon \approx 9 \times 10^2$). A quantitative uv-vis spectra of the iron chloride complex (Figure 2) was also recorded: Soret, 420.5 nm ($\epsilon = 1.05 \times 10^5$), β -band at 507.3 nm ($\epsilon = 1.52 \times 10^4$) and α -band at 638.9 nm ($\epsilon = 6.67 \times 10^3$). On metathesis to the triflate from the iron chloride complex (Figure 3), the Soret shifts to 396 nm with β and α bands at 515 nm, 580 nm, and 650 nm, respectively.

Low temperature uv-visible spectroscopy shows the product generated by treating FeTDCPDNPPTf with mCPBA (Figure 4) has bands at 395.4 nm (Soret, $\epsilon = 1.75 \times 10^4$) and 682.7 nm ($\epsilon = 4.95 \times 10^3$), typical of tetraarylporphyrin π -cation radicals[12,13]. Addition of 1-methyl imidazole (1-MeIm, Figure 5) generated a species with bands at 422.8 nm (Soret, $\epsilon = 1.77 \times 10^4$), and 548 nm ($\epsilon = 3.63 \times 10^3$), typical of one-electron-reduced oxoferryl complexes. The uv-vis showed that the Fe(IV) complex was stable overnight and that the oxoferryl porphyrin π -cation radical species was stable for at least twenty minutes at -80°C . The stability of the high valent complexes is noteworthy as some high valent complexes are not stable beyond a few minutes.

Both ambient and low temperature $^1\text{H-NMR}$ studies were performed on FeTDCPDNPPTf. The $^1\text{H-NMR}$ spectra are shown along with that of the free base (Figure 6). Four pyrrole protons, 12-H, 13-H, 17-H, 18-H, appear as a broad singlet overlapping with a two proton doublet, 2-H,8-H, from AX quartet of the remaining pyrrole hydrogens; the second AX doublet, 3-H,7-H, is at 8.6 ppm. The proton signals from the 2,6-dinitrophenyl substituent show substantial down-field shifts as expected. In addition, the free base showed two hydrogens at -2.50 ppm (bs, 2 H, H-pyrrole nitrogens), as expected.

The low temperature $^1\text{H-NMR}$ spectra showed that the oxoferryl porphyrin π -cation radical was generated (Figures 7 & 8). The proton signals from the pyrroles were shifted to extremely high-field (-56, -58 ppm) relative to those reported for the TMP

oxoferryl π -cation radical (-33.2 ppm) [13]. This upfield position suggests large unpaired electron spin density on the pyrrole β -carbons, and from the illustration of a_{1u} and a_{2u} , large unpaired electron spin density on the β -carbons suggests a_{1u} character.

EPR studies (Figure 9) of the oxidized FeTDCPDNPPTf show a rhombic spectrum, indicating inequivalent x- and y-axes, similar to the spectrum of the oxoferryl tetramesitylporphyrin π -cation radical. The g values, $g_{||} = 1.99$ and $g_{\perp} = 4.13, 3.65$ ($g_{\perp}^{eff} = 3.89$), clearly demonstrate that the oxoferryl porphyrin π -cation radical exhibits strong ferromagnetic coupling between the unpaired porphyrin electron and the unpaired iron electron.

Resonance Raman studies (Figure 10) show ν_2 and ν_4 at 1557 and 1365 cm^{-1} , respectively, on room temperature studies at 4067Å during parallel studies. On oxidation, ν_2 shows little shift (in contrast to the a_{2u} oxoferryl tetramesityl porphyrin π -cation radical). This behavior is consistent with admixture of a_{1u} character, as suggested by NMR.

TPFPCl₈PP:

The uv-vis spectra for the perhalogenated porphyrin, TPFPCl₈P, are shown in Figures 12- 19. The free base, TPFPPH₂ (Figure 12), is shown as a reference, along with the zinc complex (Figure 13). The uv-vis spectra showing that ZnTPFPCl₈P was generated is shown in Figure 14, and the free base and iron chloride complex are shown in Figures 15-16. All available compound was used in oxidation experiments (Figure 17). Because the high-valent complex was not successfully generated, an oxoferryl porphyrin π -cation radical has not yet been characterized by NMR (¹³C or ¹⁹F), quantitative uv-vis or resonance Raman spectroscopy.

Other spectra that are included are the ^{13}C -NMR and the ^{19}F -NMR of $\text{ZnTPFPCl}_8\text{P}$ (NMR in Figures 18 & 19) and MS of both $\text{ZnTPFPCl}_8\text{P}$ and $\text{TPFPCl}_8\text{PH}_2$ (Figures 20 & 21, respectively). Once the TPFPH_2 is chlorinated, the product has no protons, so a different nucleus must be chosen for the NMR. Primary concern was that the porphyrin was fully chlorinated at the β -positions. Evidence that the chlorination was successful was shown by an 400MHz ^{19}F -NMR on the zinc complex (Figure 18) which had only three signals, as all phenyls are equivalent: -137.7 ppm (d, *p*-fluorine), -162.0 ppm (t, *m*-fluorines), and -150.05 ppm (t, *o*-fluorines). In addition, a 100MHz ^{13}C -NMR on the same complex (Figure 19) showed: all β -carbons to be equivalent (148.3 ppm), all α -carbons to be equivalent (144.7 ppm), and all *meso*-carbons to be equivalent (d, 112.66 ppm, $J=3.8$). The phenyl carbon peaks were: the *para*- carbon (multiplet, centered at 139.67 ppm), the *meta*-carbons (d, 142.10 ppm, $J=8.8$), the *ortho*-carbons (d, 137.14 ppm, $J=18.6$) and the tertiary-carbon (t, 145.92 ppm).

Finally, mass spectrometry also confirmed that the porphyrin was successfully generated. The characteristic pattern for the stable chlorine isotopes and the correct molecular ion is evident the mass spectra. Only the zinc complex (Figure 20) and free base (Figure 21) are shown, as the mass spectrum of the iron complex has not yet been recorded.

Conclusions

It was postulated that addition of electron-withdrawing substituents on the meso-phenyl rings would lead to weakened ferromagnetic coupling between the unpaired ferryl electrons and the unpaired porphyrin electron. Although this porphyrin seems particularly stable in its catalytically active form, coupling appeared to be qualitatively similar to that reported for TMP, which is considered to be a "strongly" coupled oxoferryl porphyrin π -cation radical. This means that the a_{1u} admixture does not sufficiently perturb unpaired spin density on the porphyrin to affect its coupling with the ferryl iron. Support for this explanation is provided by the oxoferryl porphyrin π -cation radical generated from 2,7,13,18-tetramesityl-3,8,12,17-tetramethyl porphyrin, which is expected to be in a "pure" a_{1u} symmetry state[32]. This oxoferryl porphyrin π -cation radical shows the expected decrease in ferromagnetic coupling[45].

In addition to characterization of the oxoferryl porphyrin π -cation radical of the dinitro-derivative, an important new work-up method was developed that allows isolation of greater quantities of this porphyrin. Historically, it was thought that steric hindrance prevented successful condensation of the pyrrole and 2,6-dinitrobenzaldehyde and reported yields were 5-10mg[5]. This new work-up demonstrates that the condensation is not inhibited, but that the porphyrin is easily lost on columns. Yields in this new method were five to ten fold higher than previously reported methods.

While the perhalogenated porphyrin appears to be an interesting complex, work is still incomplete.

Suggestions for Future Studies

Although the TDCPDNPP is interesting in its own right, preliminary attempts were made to generate a di-"picket fence" porphyrin from the TDCPDNPP. This entails first reducing the nitro- groups to amines and then acetylating them with the desired "picket", either a pivaloyl or trifluoro acetyl. The pickets are interesting because they crudely simulate the amino acid backbone of the heme protein. Preliminary evidence from work on the trifluoroacetamido picket [unpublished] suggests a hydrogen is rapidly abstracted from the picket group by the oxo-oxygen upon generation of the oxoferryl porphyrin π -cation radical. If this is demonstrated, it can be concluded that the "picket fence" porphyrins are not good models for active sites of enzymes acting through compound I-type transients.

Monopicket complexes with pivaloyl and trifluoroacetamido groups have already been made by this lab from 5-(2-chloro,6-nitrophenyl)-10,15,20-tris(2,6-dichlorophenyl)porphyrin (TDCPMNPP). Synthesis of the di-picket is important, because in the case of the monopicket, some proportion of the picket may be oriented on the opposite face of the porphyrin from the oxygen in the oxoferryl species. Therefore, one cannot conclusively demonstrate that hydrogen abstraction is the mechanism for decay of the compound I analogues in these biomimetic systems. Obviously the di-picket must have one of the pickets on the same face as the oxygen, facilitating study of such a process.

In addition to further work on the picket fence derivative of TDCPDNPP, effort should be made to continue the work with the perhalogenated TPFPCl₃PP. One suggestion is that attempts be made to directly form and study the Fe(IV) complex, the

proposed catalytically active species for these porphyrins. In addition, since the original oxidation indicated that the oxoferryl porphyrin π -cation radical was formed, further studies could employ more highly coordinating solvents or axial ligands in order to prevent bleaching. It would definitely be a significant contribution to demonstrate that these perhalogenated porphyrins can indeed go through the compound I analog active species.

Figure 1

$\text{Fe}(\text{TCPPDNPPH})_2$ (6.8×10^{-6} M)

Figure 2 -

$\text{Fe}(\text{TCPPDNPCl})$ (6.6×10^{-6} M)

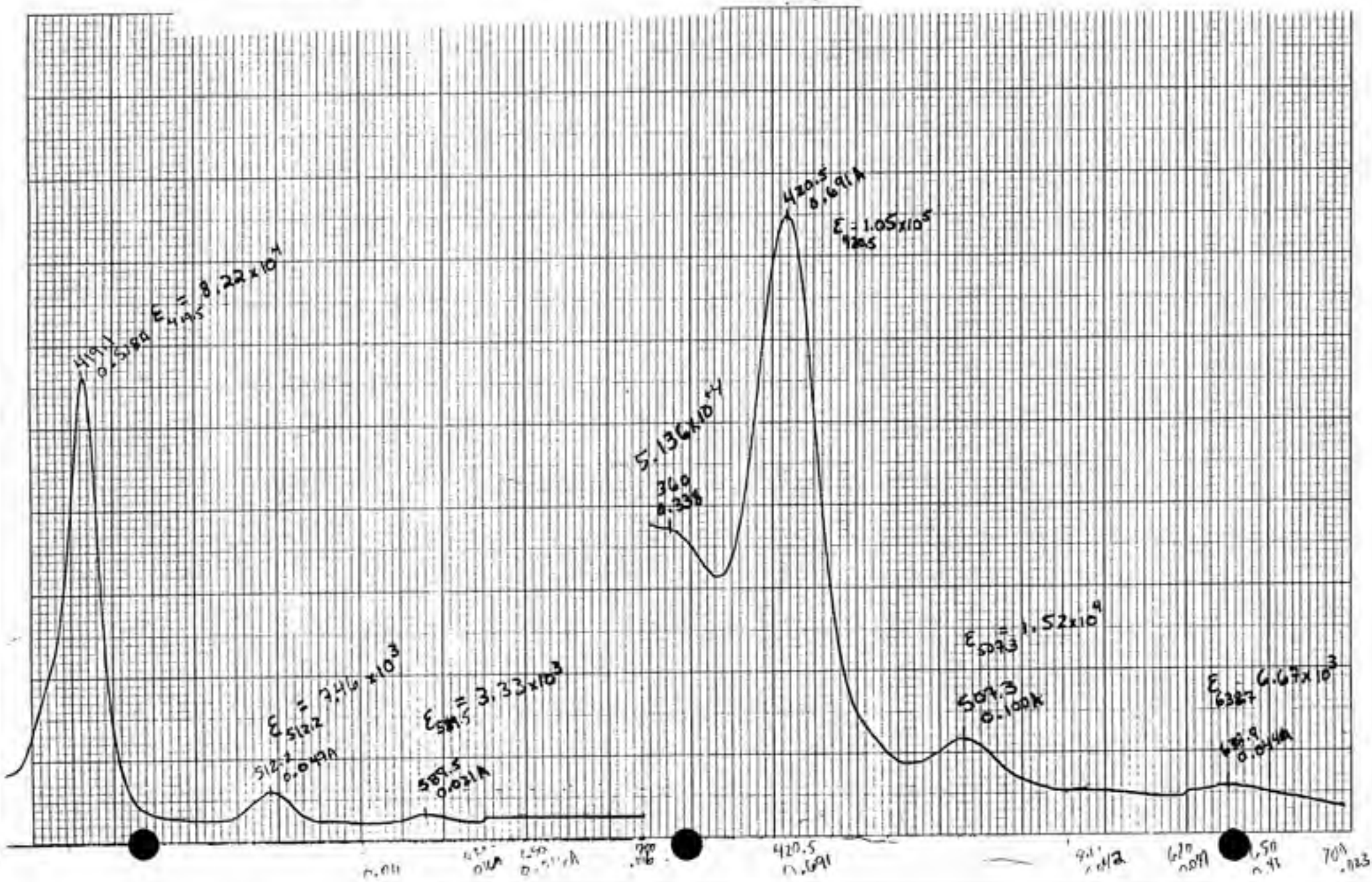


Figure 3

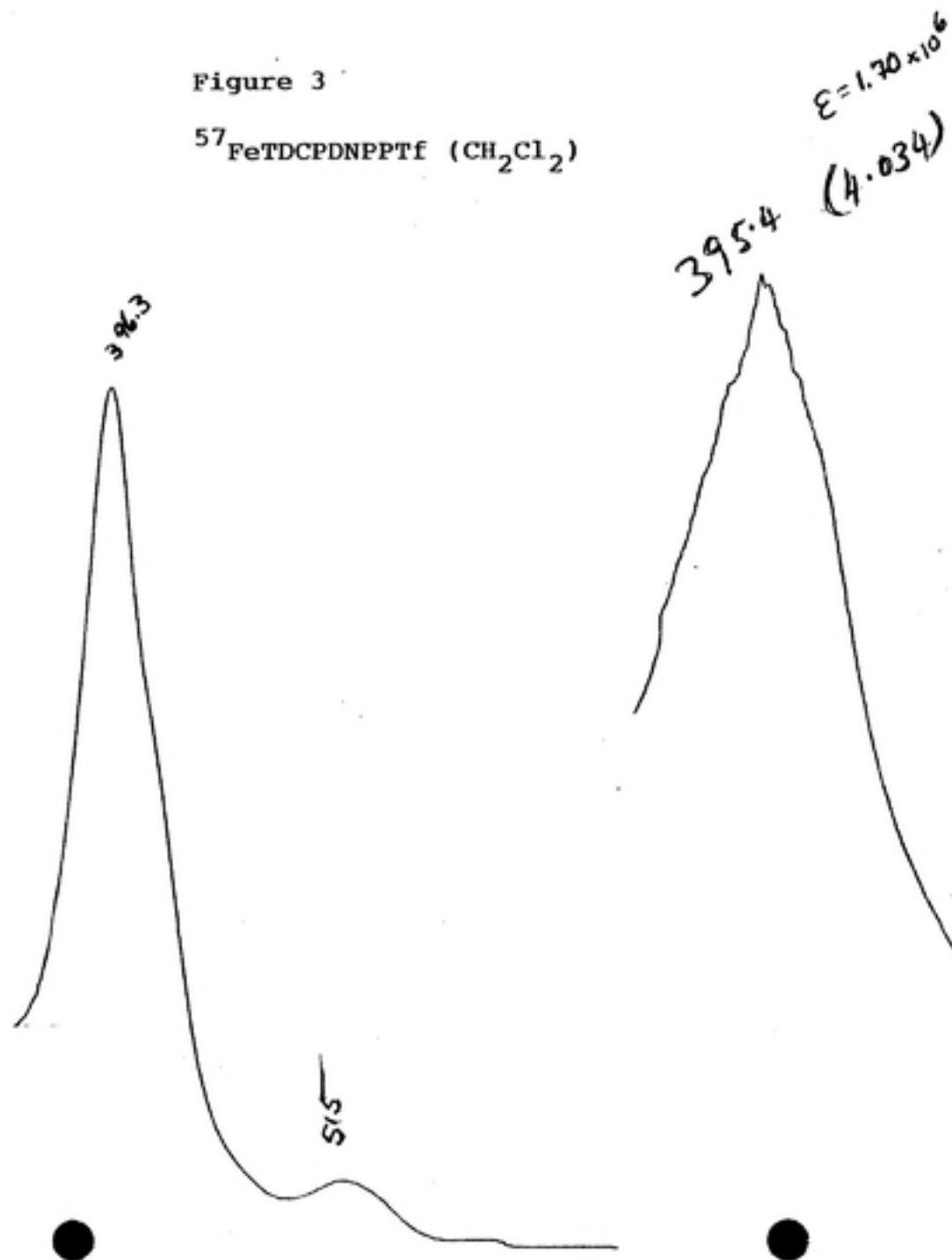
 $^{57}\text{FeTDCPDNPPTf}$ (CH_2Cl_2)

Figure 4

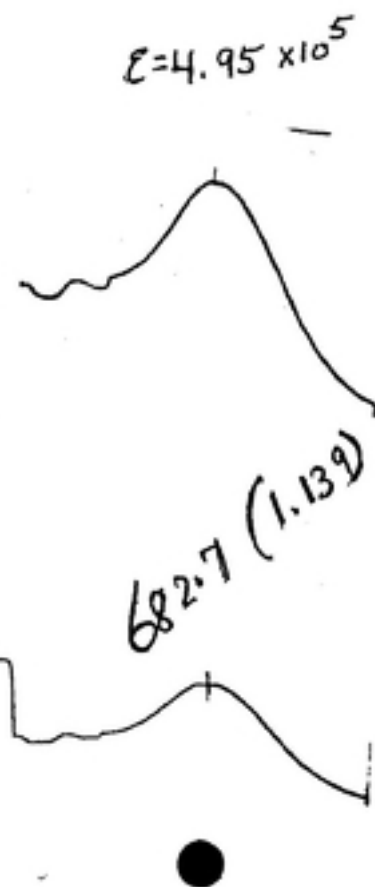
 $\text{FeTDCPDNPPTf} + \text{mCPBA}$ 

Figure 5

FeTDCPDNPTf + mCPBA + 1-MeIm
(CH₂Cl₂)

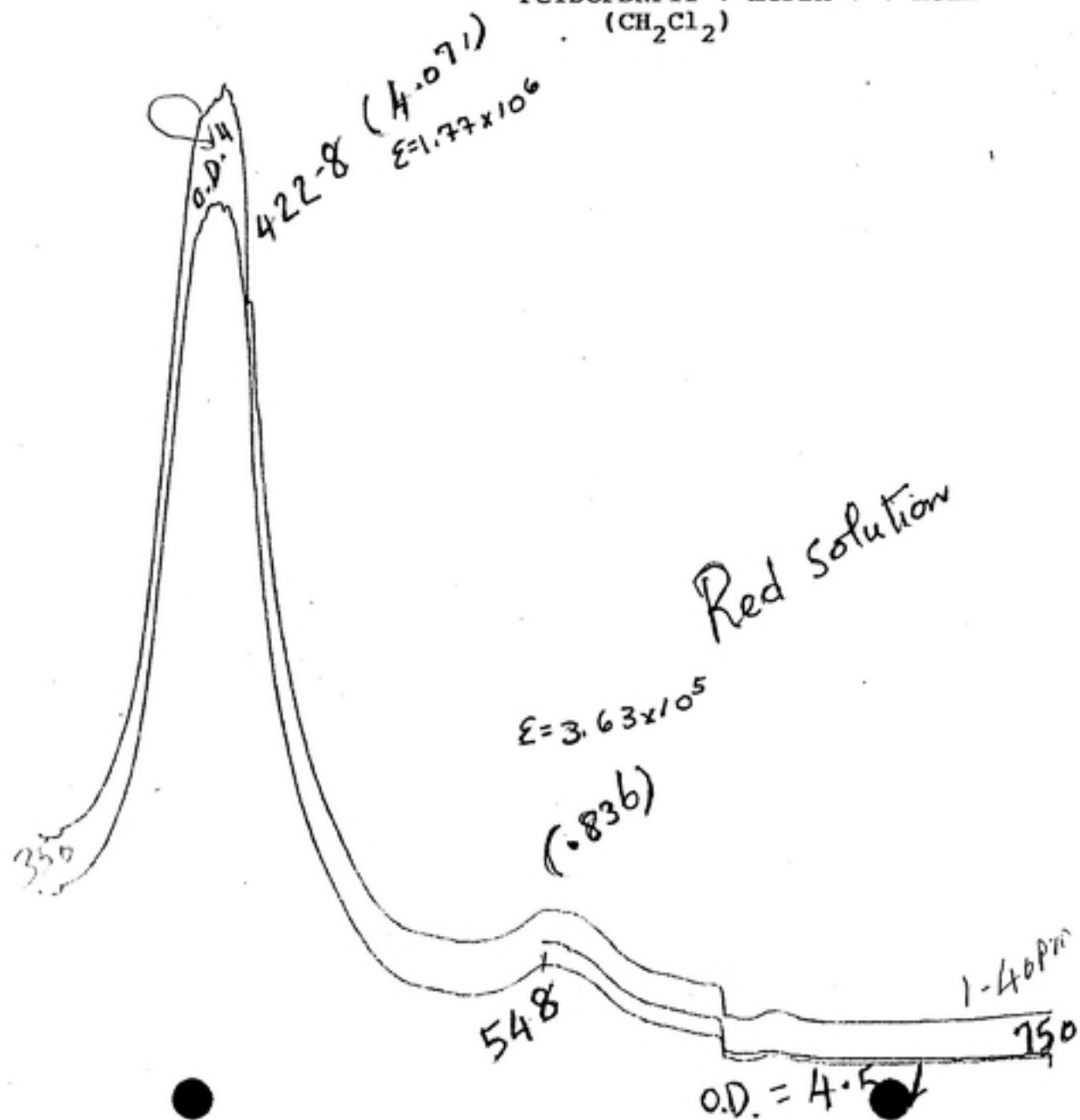


Figure 6
TDCPDNPPH₈ (CDCl₃)

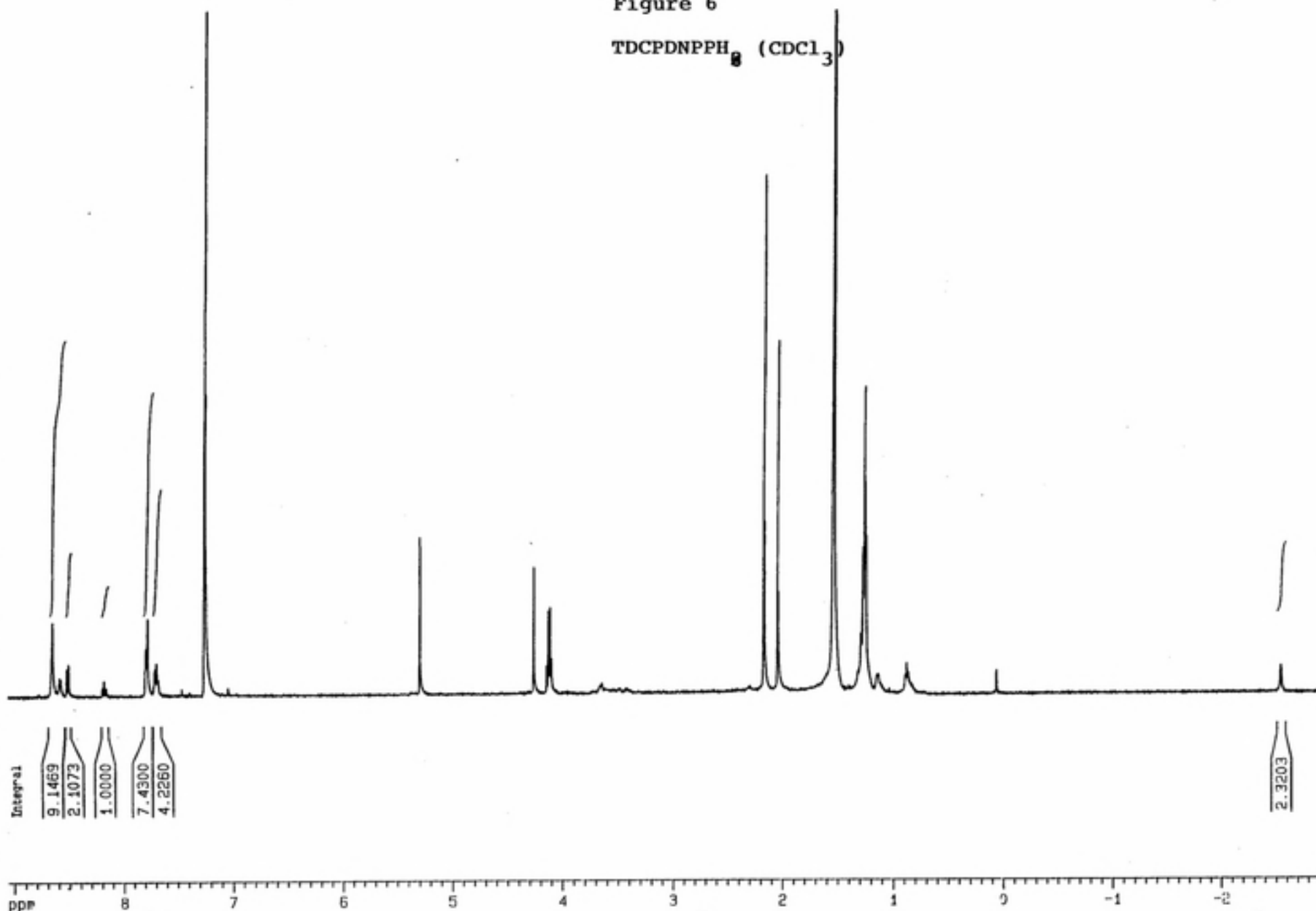


Figure 6 (cont)'

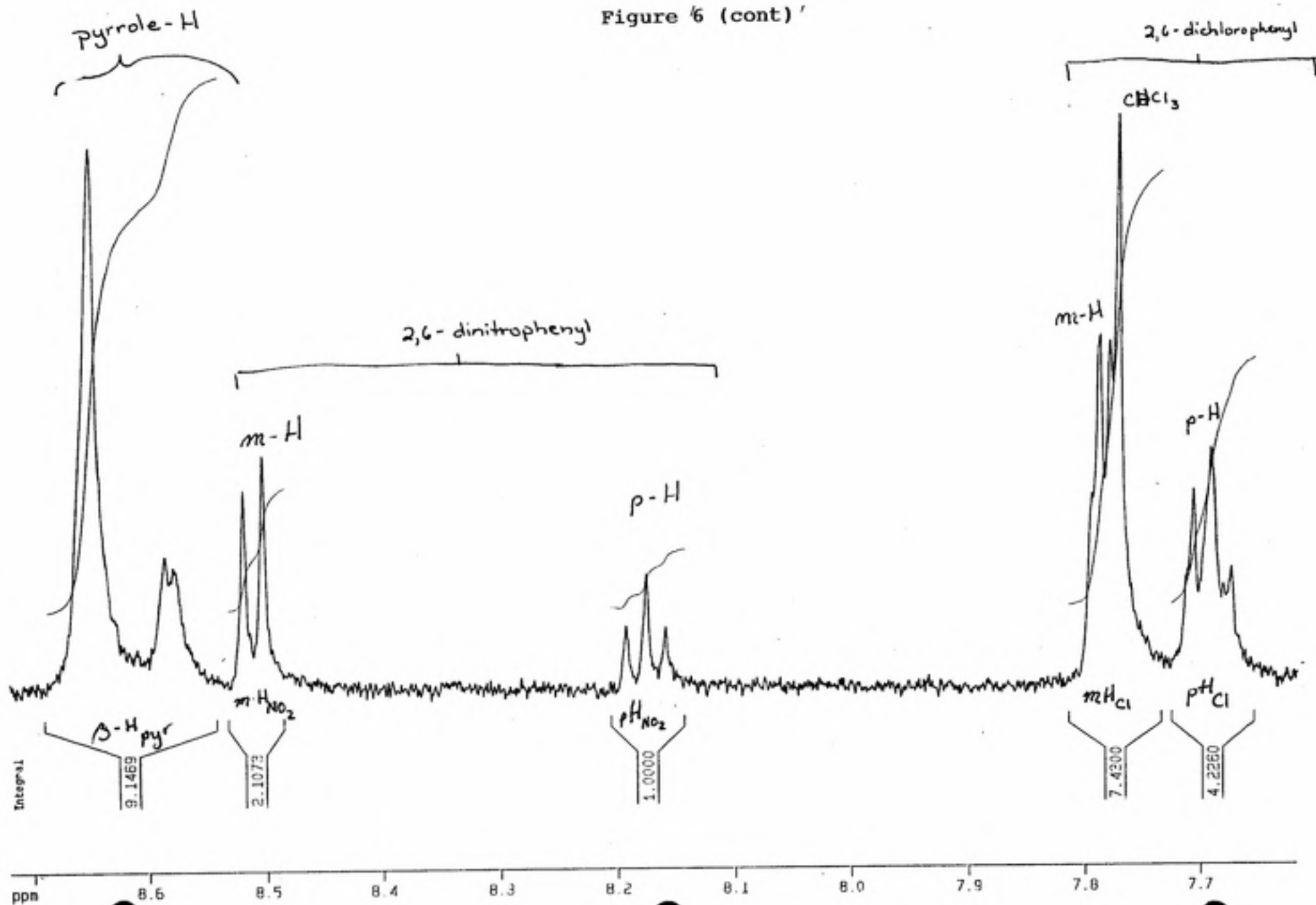


Figure 7
of dinitroporphyrin-FeT₂

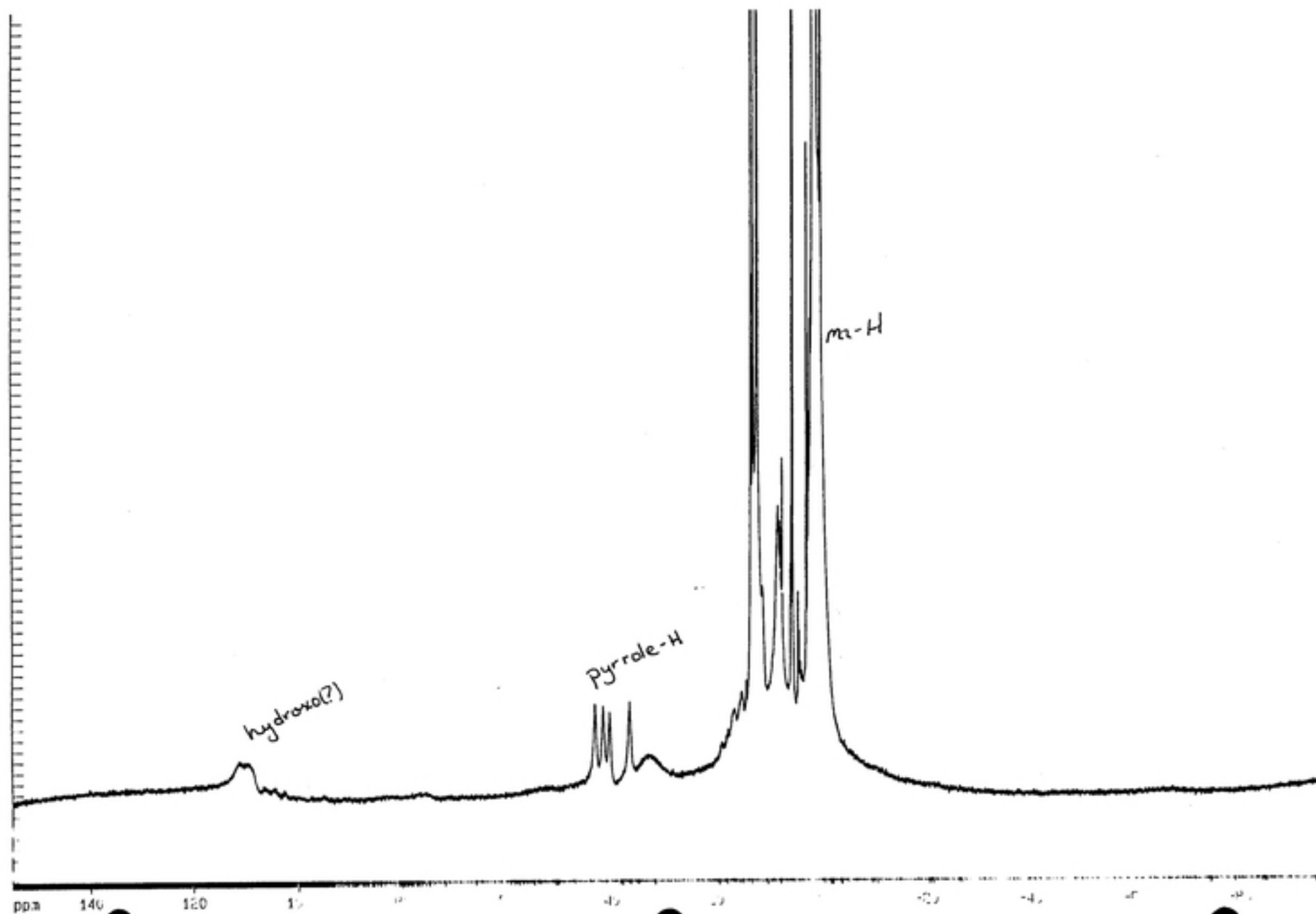
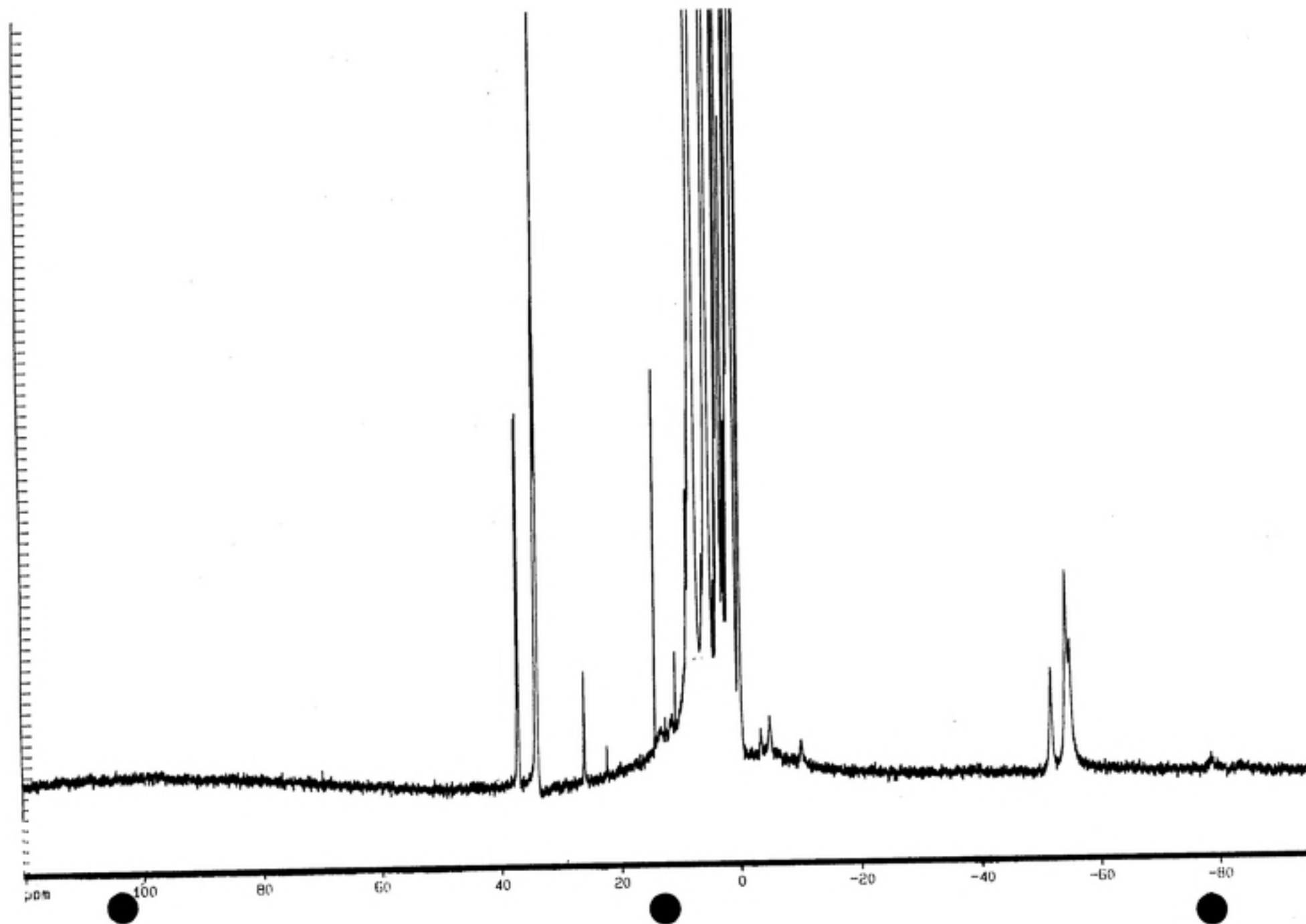


Figure 8
dr dinitroporphyrin + mcoba

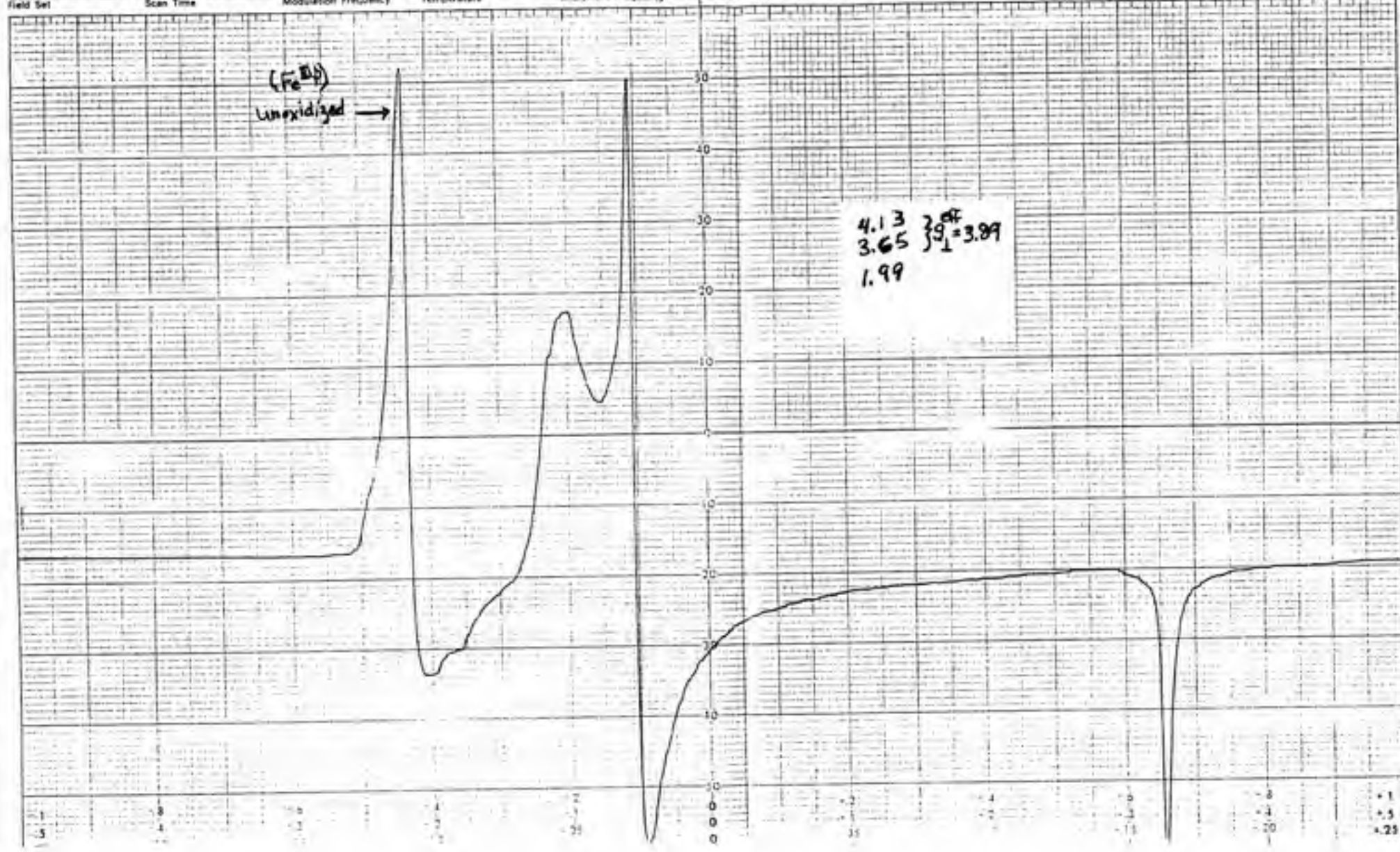


Scan Range $\star 100 \text{ G}$ Fine Constant $.064 \text{ sec}$ Modulation Amplitude 1.2 G Receiver Gain 2.5×10^3 Microwave Power 10.1 mW
 Field Sel 3000 G Scan Time 4 min Modulation Frequency $1 \times 10^4 \text{ Hz}$ Temperature $11.7 \text{ }^\circ\text{C}$ Microwave Frequency 9.22998 GHz

Operator RJA

Date 11/16/93

Remarks Figure 9 (FeTDCPDNPTf + MCPBA)



(FeD)
 Unoxidized →

4.13 }
 3.65 } 3.89
 1.99 }

VN 1010 (EPR CHART A)

Sample

Spectrum No.

T = 12 K

Figure 10

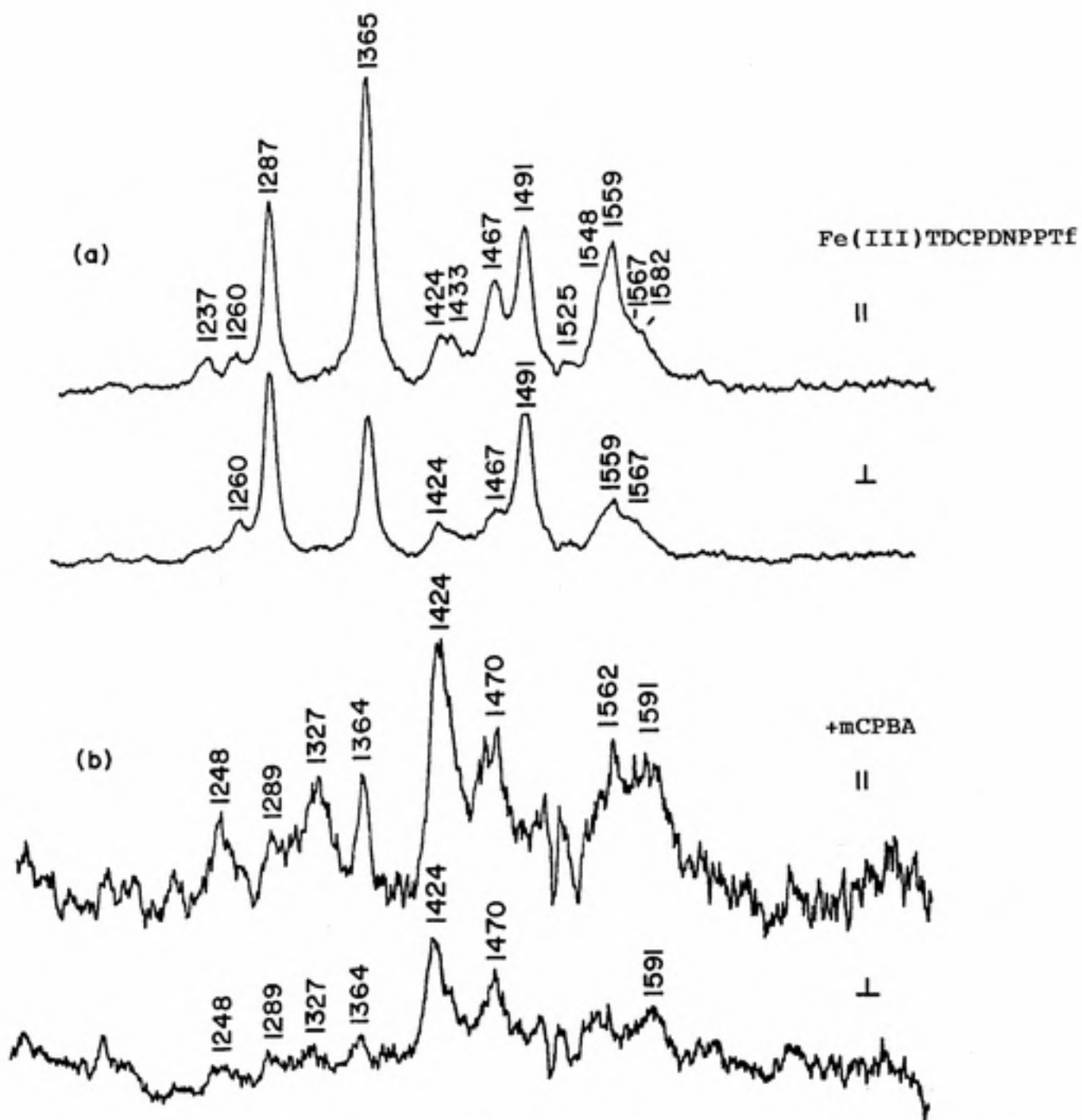


Figure 11

⁵⁷FeTDCPDNPPCl

File:V6146 Scan:2 Int Def 0.25 Acq: 9-MAR-94 15:30:34 +0:50
 70SEQ EI+ Function:Magnet BpM:154 BpI:11894784 TIC:139878144
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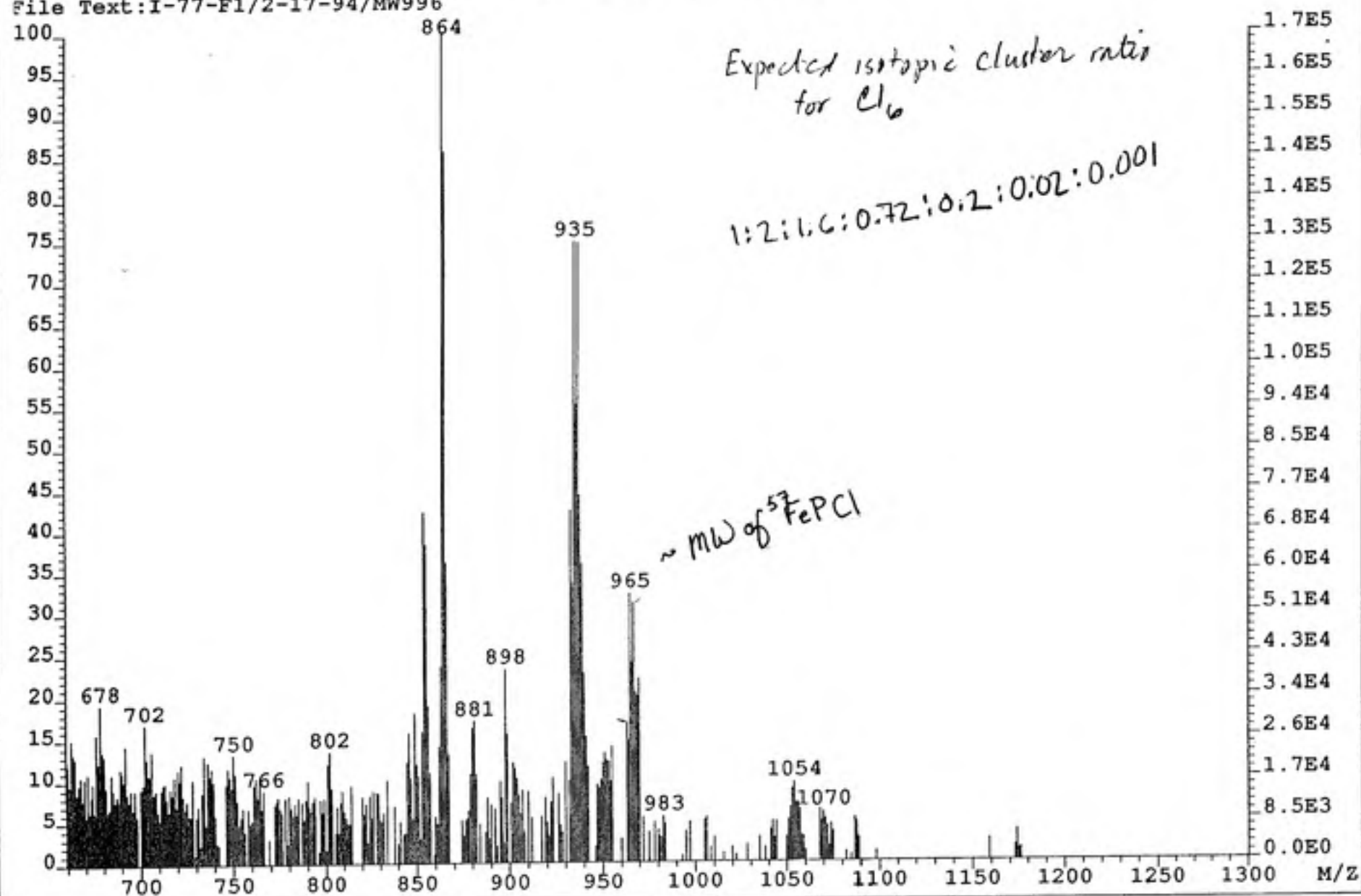


Figure 12.

TPFPH₂

409

500

541

570

620

670

Figure 13

ZnTPFP

417.9

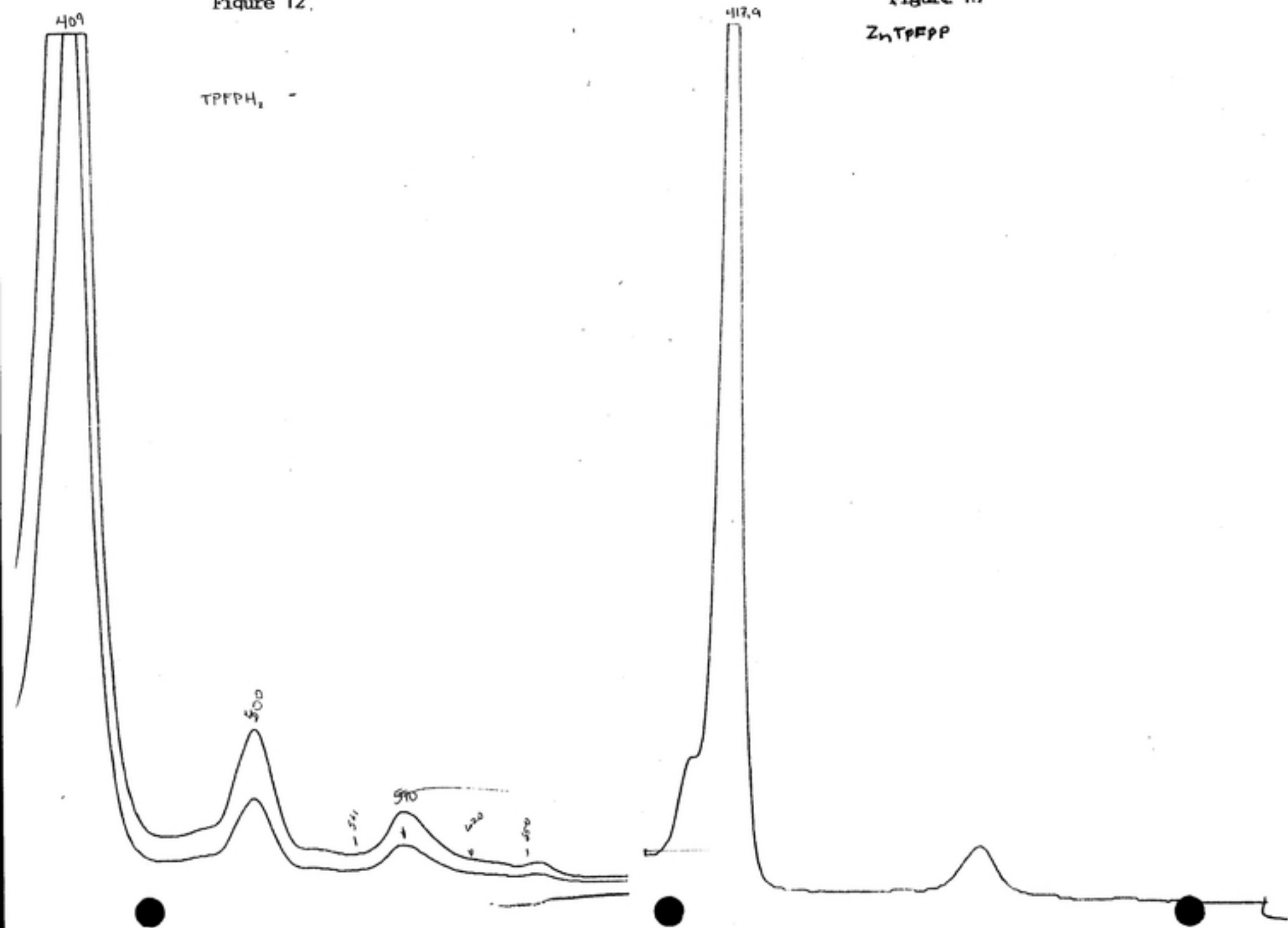


Figure 14

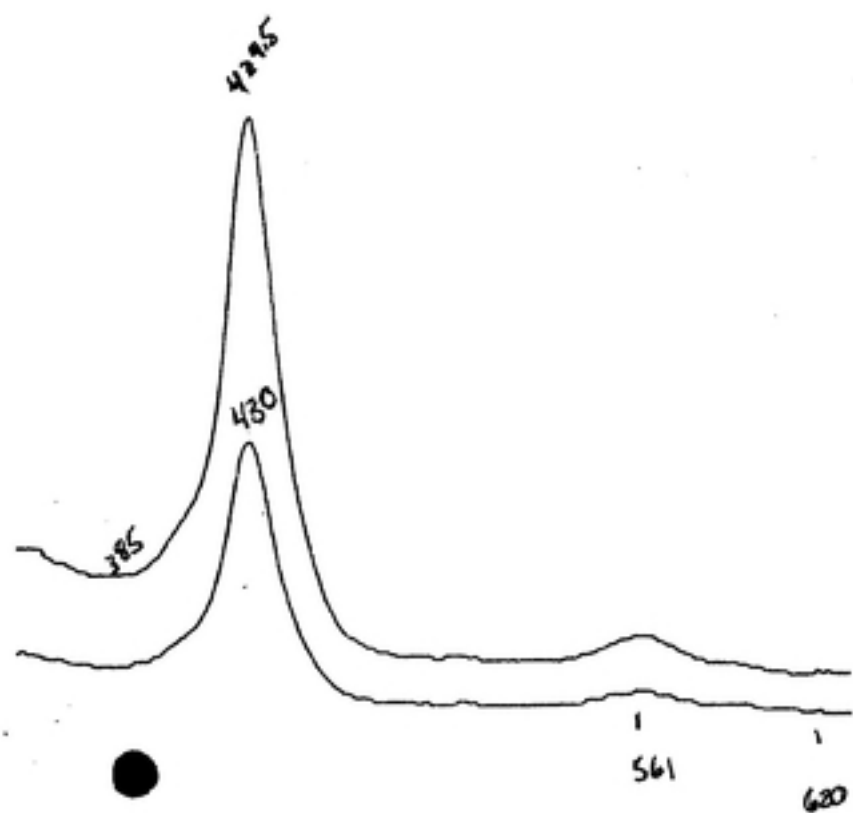
TPFPCl₈PH₂ reaction mix.(TPFPH₂ + NCS)

Figure 15

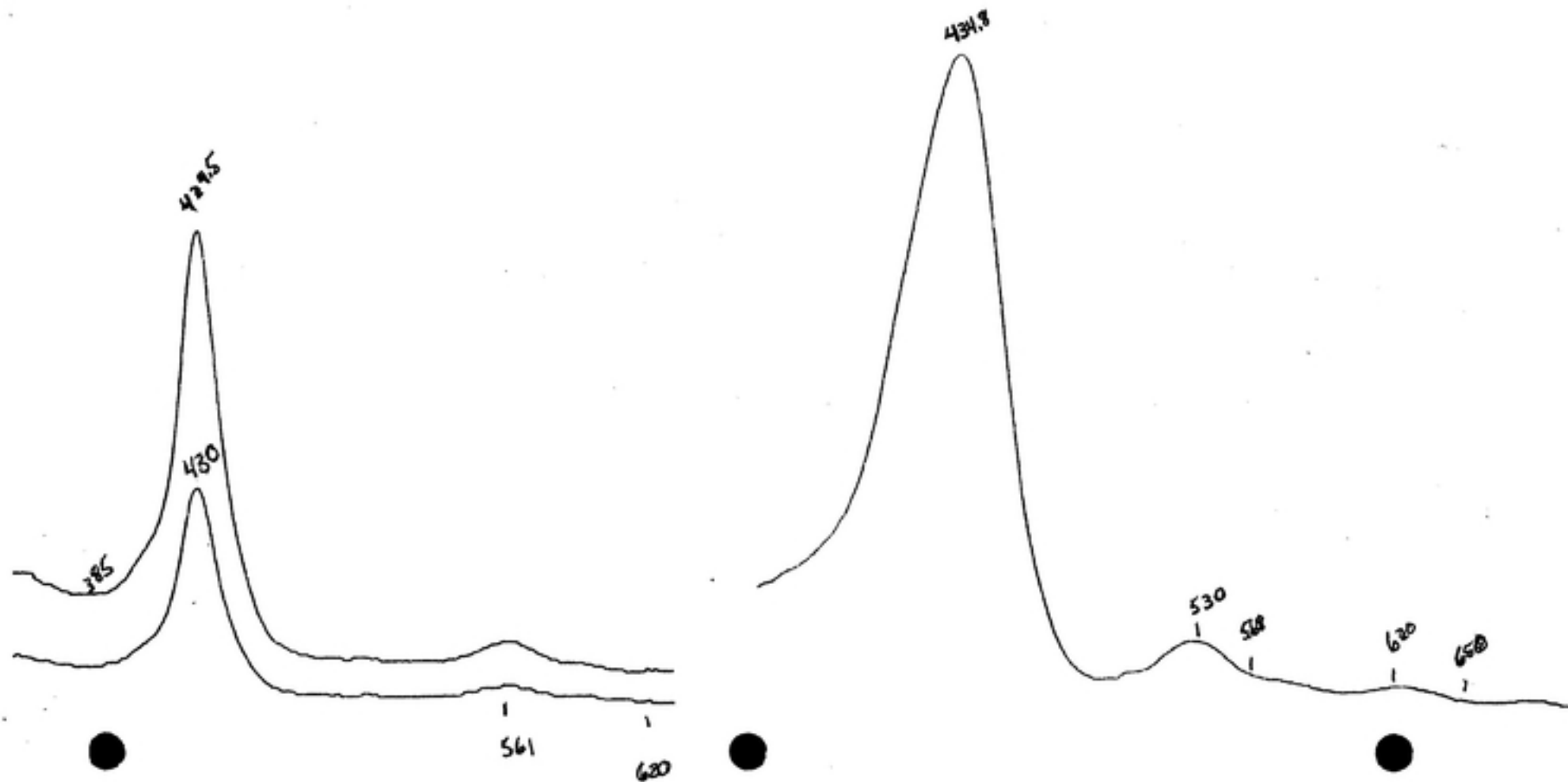
TPFPCl₈PH₂ after work-up

Figure 16
 $\text{FeTPPFCl}_8\text{PCL}$

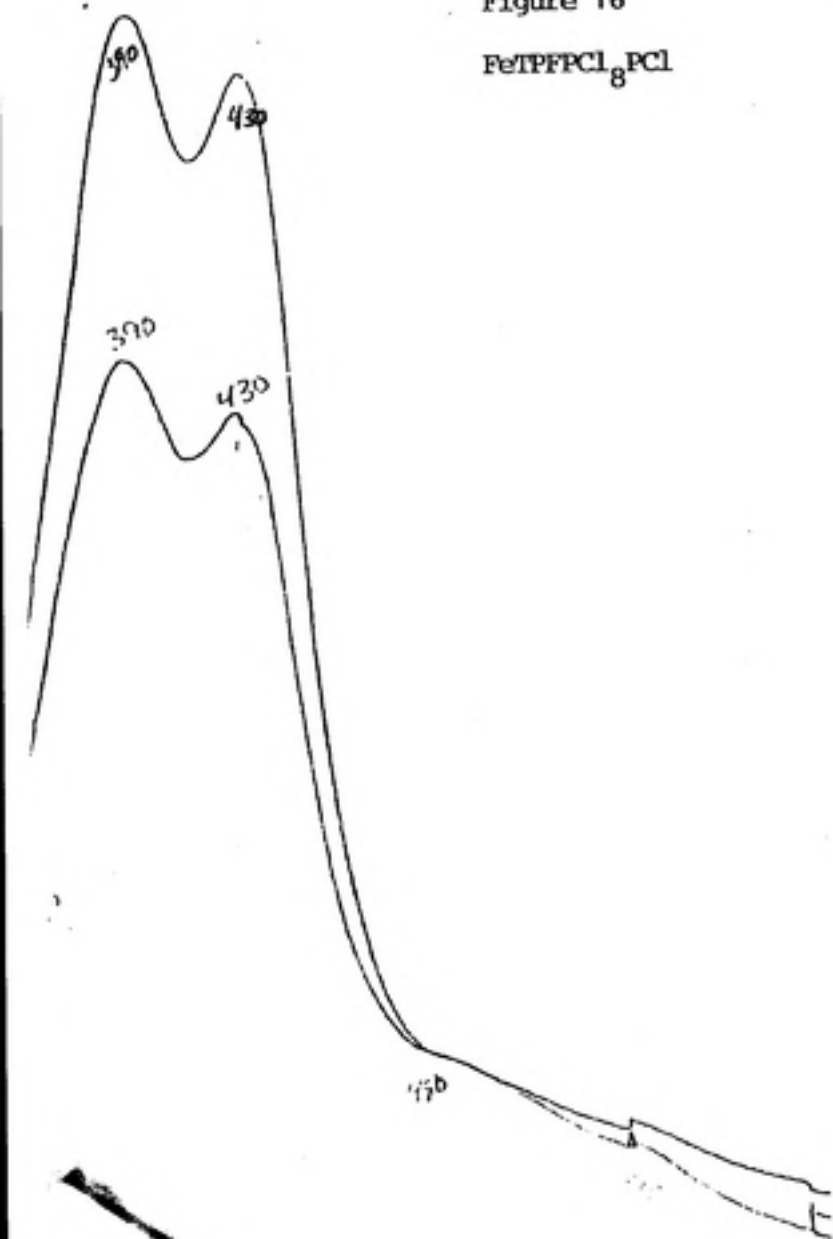
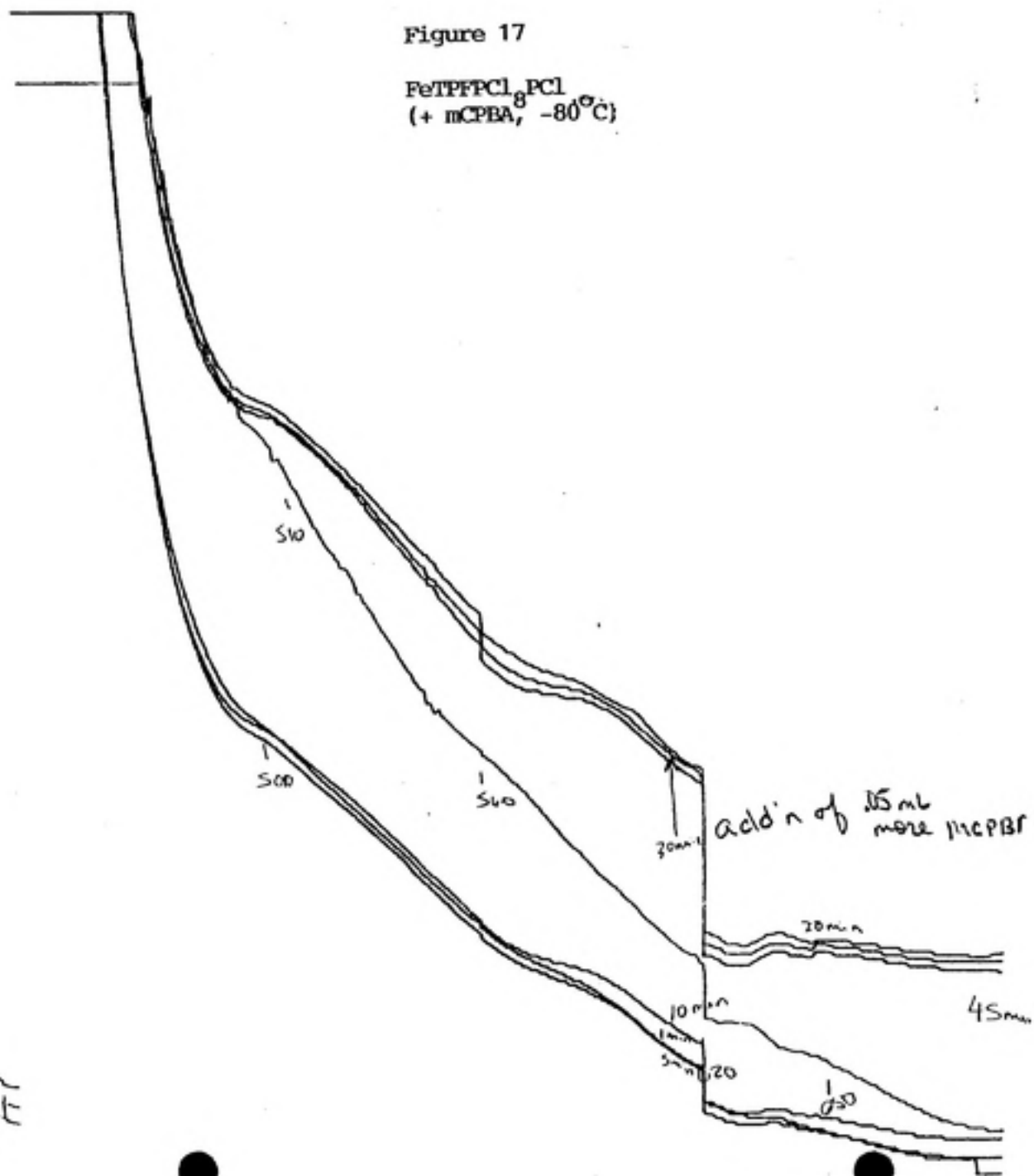


Figure 17

$\text{FeTPPFCl}_8\text{PCL}$
 (+ mCPBA, -80°C)



ZNTPFPCL8P
 DAWN ROBERTS
 EXP9 PULSE SEQUENCE: S2PUL
 DATE 07-16-93
 SOLVENT CDCL3
 FILE GOLDF

Figure 18

ZnTPFPCL₈P¹⁹F-NMR, CCl₃ external reference

OBSERVE FLUORINE
 FREQUENCY 376.27 MHZ
 SPECTRAL WIDTH 75188 HZ
 ACQ. TIME 0.426 SEC
 PULSE WIDTH 7 DEGREES
 AMBIENT TEMPERATURE
 NO. REPETITIONS 3008
 SPIN RATE 20 HZ
 DOUBLE PRECISION ACQUISITION
 DATA PROCESSING
 LINE BROADENING 2.5 HZ
 FT SIZE 64K
 TOTAL TIME 21.3 MINUTE

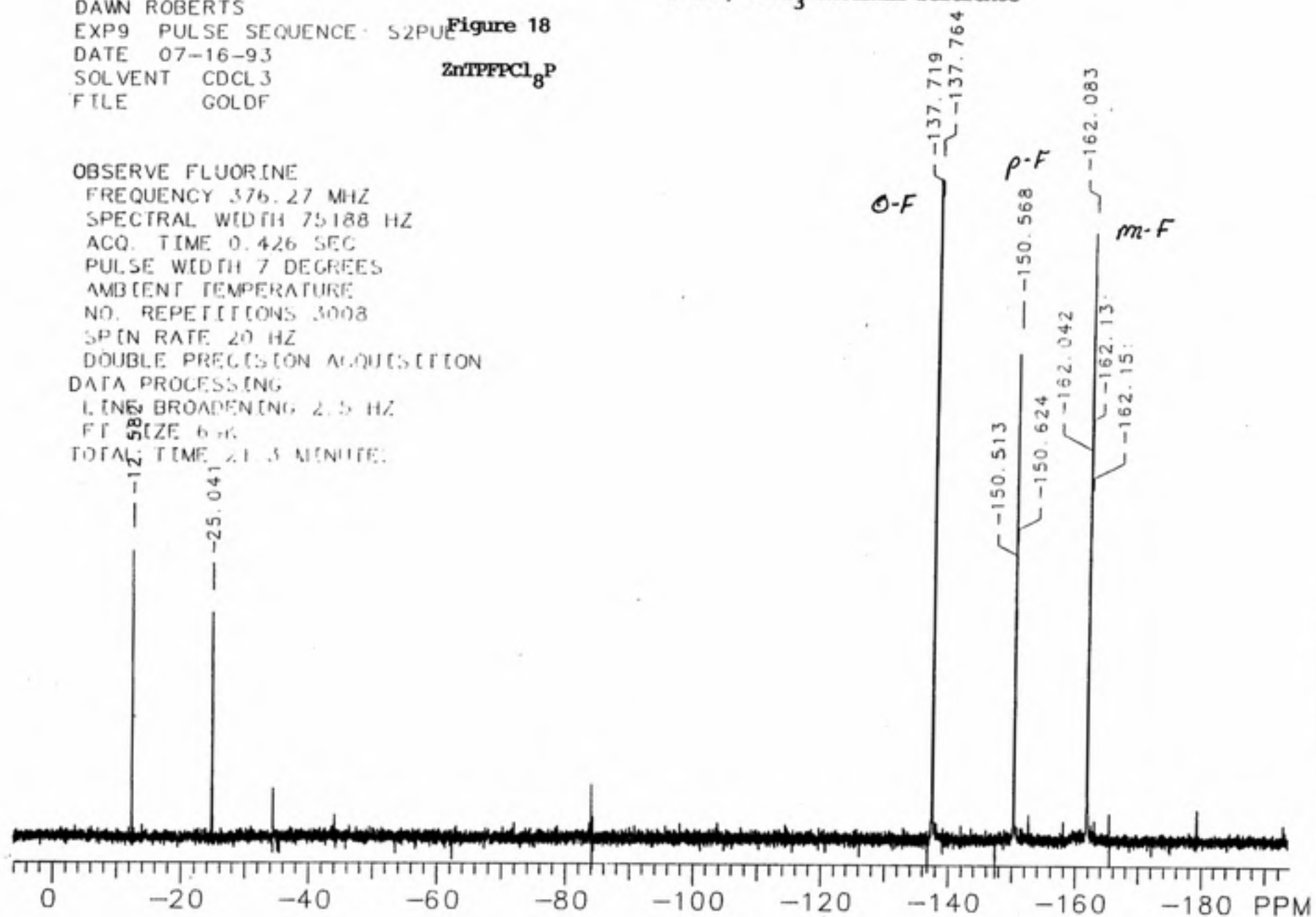
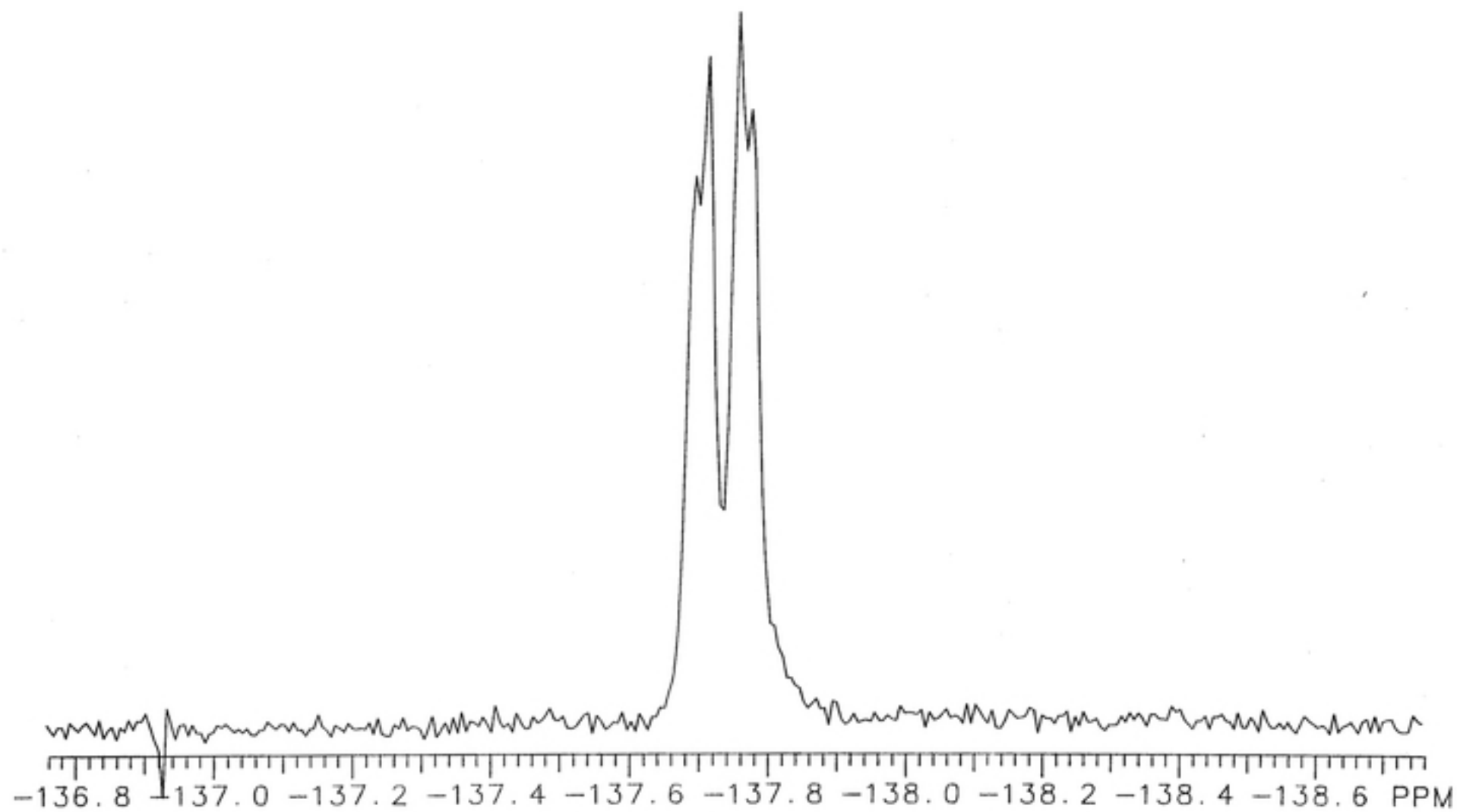


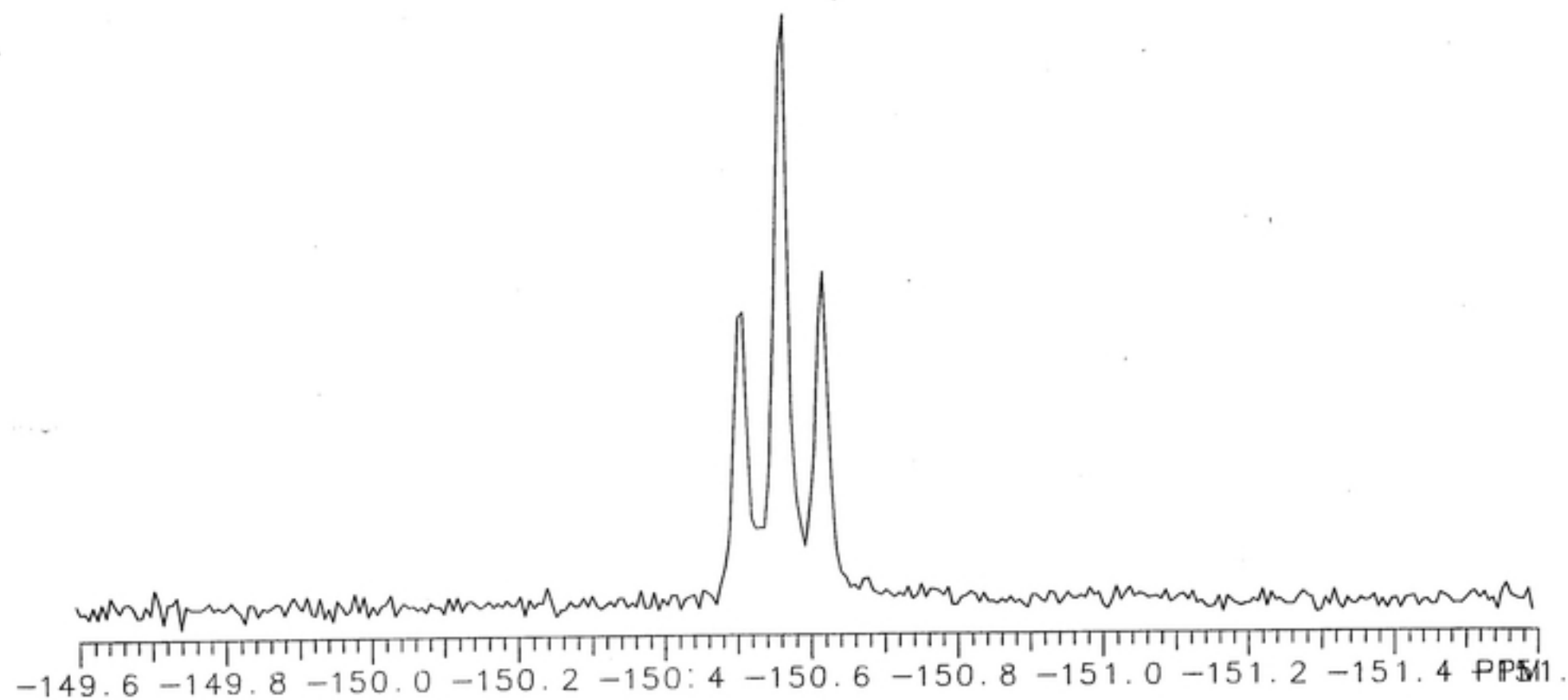
Figure 18

o-F expansion



o-F

Figure 18
p-F expansion



● F

●

●

Figure 18
m-F expansion

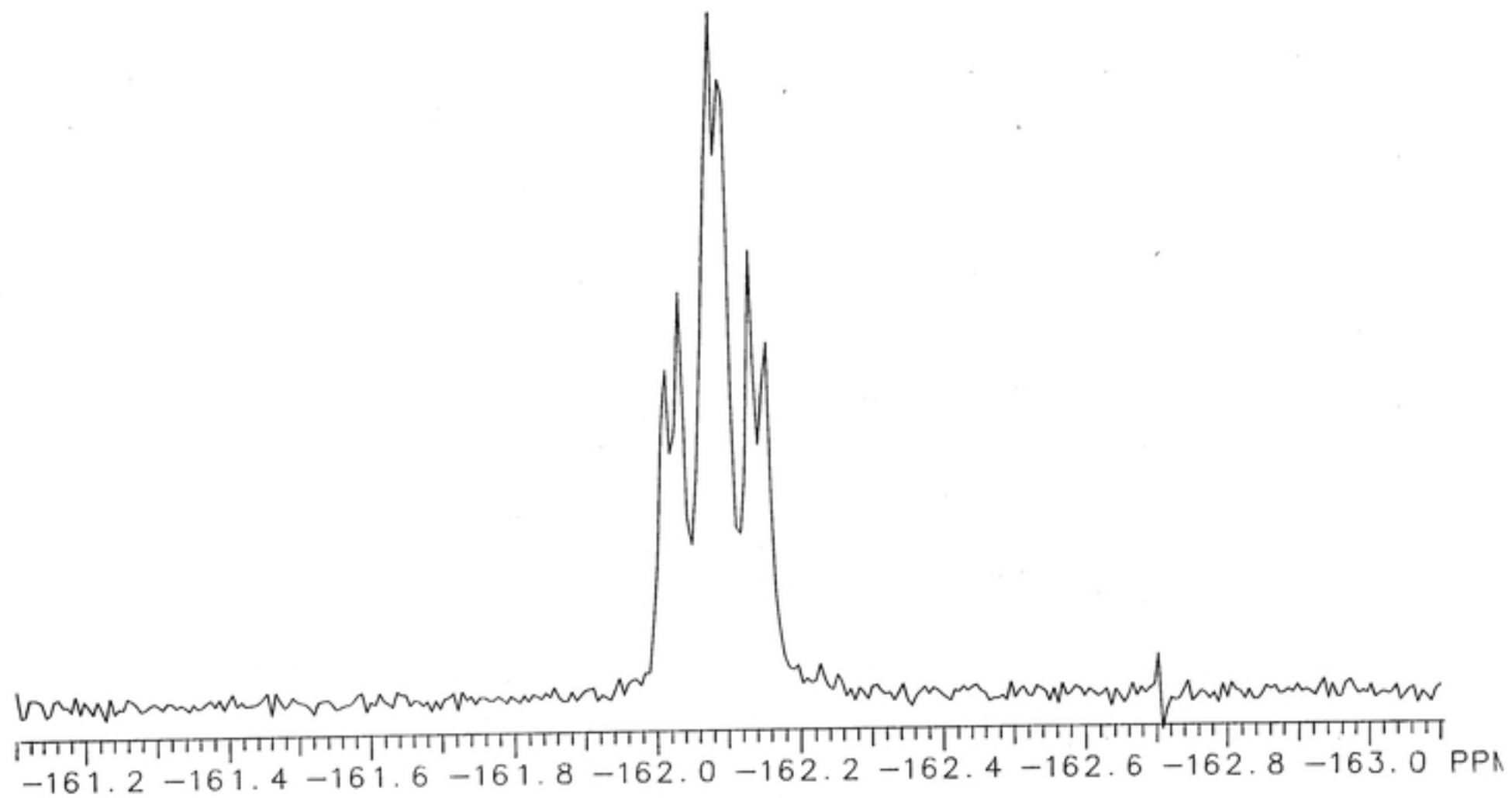
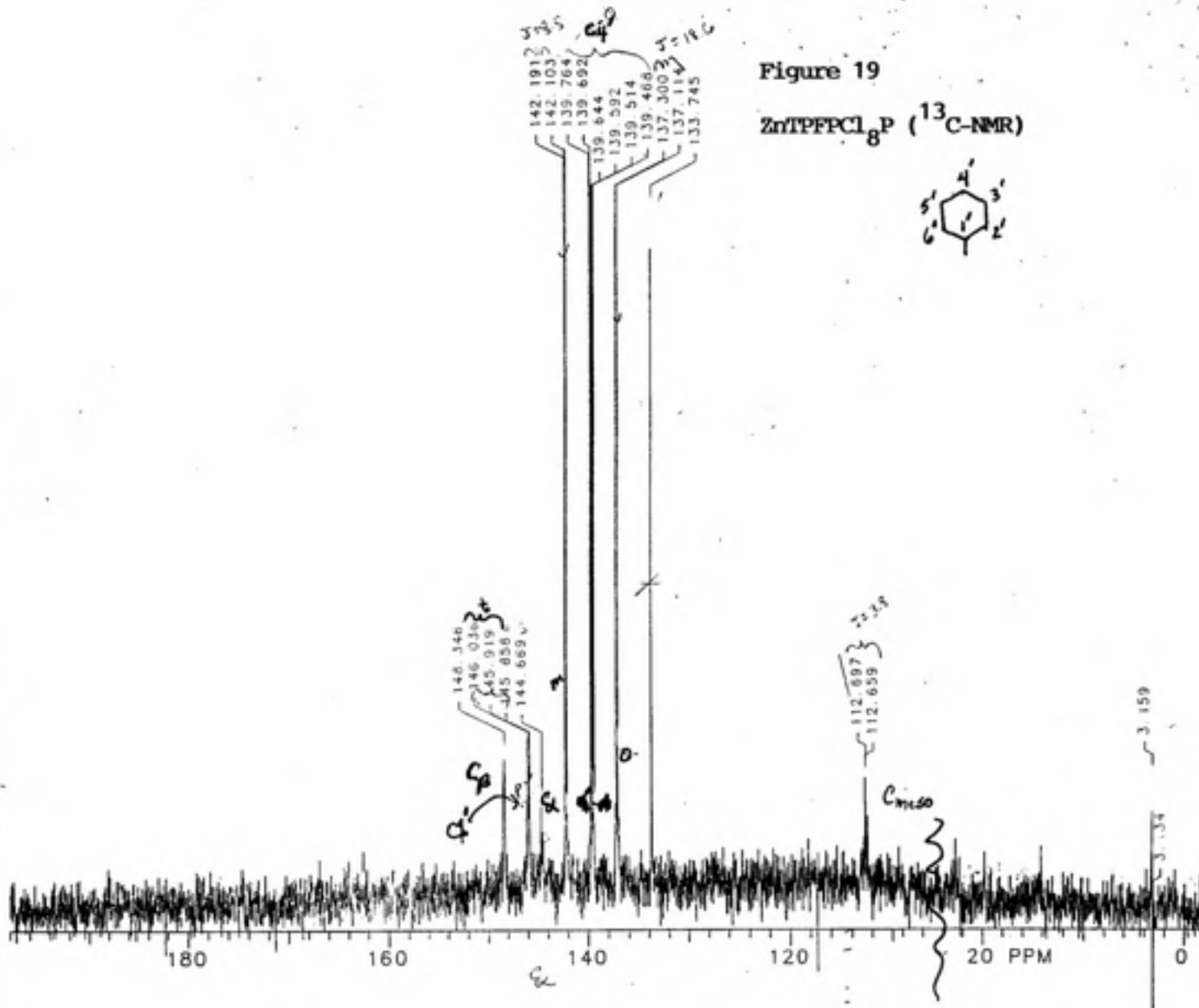
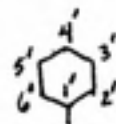


Figure 19

ZnTPFPCL₈P (¹³C-NMR)

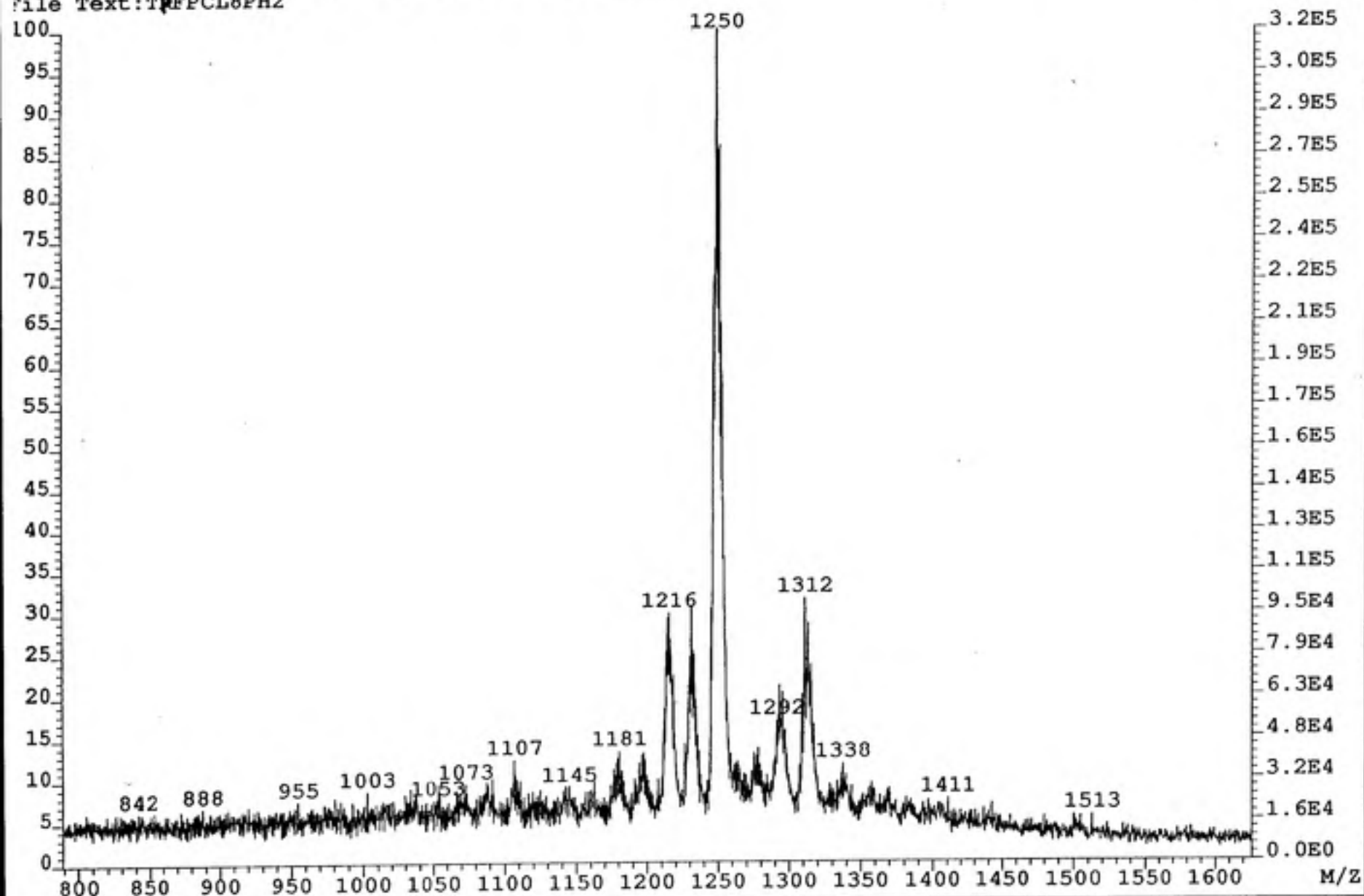
ZNTPFPCL8P
 DAWN ROBERTS
 EXP2 PULSE SEQUENCE STD13C
 DATE 07-19-93
 SOLVENT CDCL3
 FILE C

OBSERVE CARBON
 FREQUENCY 100 MHz
 SPECTRAL WIDTH 20000 Hz
 ACQ TIME 0.663 SEC
 PULSE WIDTH 30 DEGREES
 AMBIENT TEMPERATURE
 NO. REPEATS 8000
 GATED DECOUPLING
 SFTV FACT 40 Hz
 DIGITAL PRECISION ACQUISITION
 DATA PROCESSING
 LINE BROADENING 2.3 Hz
 FT 2000 Hz
 TOTAL TIME 14 HOURS
 44.5 MINUTE

Figure 20

MW (ZnTPPCL₈P) = 1312 g/mole
MW (TPPCL₈PH₂) = 1250 g/mole

File:V8872 Scan:1 Acq:14-FEB-95 12:25:48 +0:48
70SEQ FAB+ Function:Magnet BpI:39820 TIC:35971708
File Text:TPPCL8PH2



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