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A comparative mechanistic study of the oxidation of phenols in aqueous solution by oxomanganese(IV) and oxoiron(IV) 5,10,15,20-tetrakis(2-*N*-methylpyridyl)porphyrin

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Abstract

The kinetics of the reactions of phenol and six substituted phenols with oxomanganese(IV) tetra(2-*N*-methylpyridyl)porphyrin in aqueous solution (pH 7.7) have been studied. The reactions are shown to be first order in both phenol and the oxomanganese(IV) species. The second order rate constants have been measured and the influence of the substituents on these values have been analyzed using Hammett and modified Hammett equations. The magnitude of the ρ values obtained and the good correlation of the data with $\sigma^{\cdot}$ and the dual parameter $\sigma^{\cdot} + \sigma^{+}$ suggest that, like the reactions of the analogous oxoiron(IV) tetra(2-*N*-methylpyridyl)porphyrin, the rate-determining step in these oxidations involves hydrogen atom abstraction from the phenol by the oxomanganese(IV) species in which the transition state has partial charge separation.

Keywords: Hammett equations; Monopersulphate; Oxidation; Iron; Manganese; Oxo complexes; Peroxidase; Phenol; Porphyrin

1. Introduction

The role and function of the iron porphyrin prosthetic groups in the haemoprotein catalyzed oxidations of cytochrome P450 monooxgenases and peroxidases have been widely studied in the last 10–15 years [1]. This in turn has led to the development of synthetic metalloporphyrin models capable of mimicking the enzymatic oxidations [2]. Developing the potential of these systems to bring about selective oxidations is an active area of current research.

Although all the haemoproteins above contain an iron porphyrin prosthetic group, a large amount of interest has also been directed towards manganese porphyrins. Thus substitution of manganese for iron in cytochrome $P450_{cam}$ [3] and in horseradish peroxidase (HRP) [1] [4] leads to functional enzymes

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[1] The following abbreviations are used, T2MPyP and T4MPyP for tetra(2-*N*-methylpyridyl)porphyrin and tetra(4-*N*-methylpyridyl)porphyrin ligands, respectively; HRP for horseradish peroxidase.

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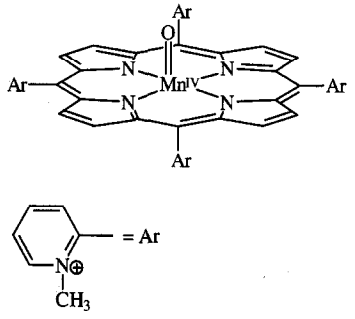


Fig. 1. Structure of OMn(IV)T2MPyP.

with reduced catalytic activity. In model systems manganese porphyrins will catalyze most of the oxidations brought about by the haem enzymes. In particular, manganese porphyrins have been extensively studied as models for cytochrome P450 monooxygenases [2](a),[5]. These investigations have led to a wide range of manganese porphyrin catalysts for the epoxidation of alkenes and the hydroxylation of unactivated C–H bonds using dioxygen or mono-oxygen donors, such as OCl^- or H_2O_2 [2](a),[5](f),[6].

The main active oxidant in these systems is the oxomanganese(V) porphyrin, although under some circumstances oxomanganese(IV) porphyrins can also be formed and participate in oxidations [7]. These species can be considered as manganese porphyrin models for peroxidase compounds I and II, respectively.

In a recent paper we reported a kinetic study of phenol oxidation in aqueous solution by OFe(IV)T2MPyP [8]. A Hammett analysis of the kinetic data showed that this HRP compound II analogue oxidizes phenols by hydrogen atom abstraction, in contrast to the enzyme where oxidation occurs by electron-transfer. We now report a kinetic study of phenol oxidation by OMn(IV)T2MPyP (Fig. 1) and compare the reactions of the oxoiron(IV) and the oxomanganese(IV) species.

2. Results

2.1. The generation of OMn(IV)T2MPyP from manganese(III) tetra(2-N-methylpyridyl)porphyrin and potassium monopersulphate

Before examining the oxidation of phenols, it was important to investigate the stability of the high-valent OMn(IV) porphyrin species in the absence of oxidizable substrates. The oxidation of Mn(III)T2MPyP to OMn(IV)T2MPyP was attempted with the oxidants t-BuO_2H, H_2O_2 and magnesium monoperphthalate. However, with none of these oxidants was it possible, in the pH range from 4–7, to obtain a good conversion to the high-valent oxomanganese(IV) porphyrin species. A UV–Vis spectroscopic study of the Mn(III) porphyrin oxidation showed that even with an excess of these oxidants only a minimal build-up of OMn(IV)T2MPyP and a slight decrease in Mn(III)T2MPyP occurred. The fact that none of the oxidants above gave a good yield of OMn(IV)T2MPyP led to the use of the more powerful oxidant potassium monopersulphate (used in the form of its triple salt $2KHSO_5 \cdot KHSO_4 \cdot K_2SO_4$ where $KHSO_5$ is the active oxidizing species). UV–Vis spectroscopy showed that the reaction of 6.0×10^{-6} mol dm^{-3} Mn(III)T2MPyP with 1.02×10^{-5} mol dm^{-3} $KHSO_5$ at 30°C, in aqueous buffer pH 7.7 and an ionic strength of 0.20 mol dm^{-3} ($NaNO_3$)

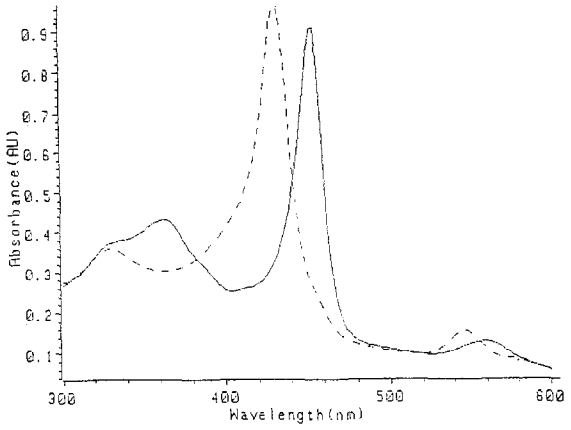


Fig. 2. UV–Vis spectrum of OMn(IV)T2MPyP (λ_{max} 424 nm) prepared from 6.0×10^{-6} mol dm^{-3} Mn(III)T2MPyP (λ_{max} 454 nm) and 1.02×10^{-5} mol dm^{-3} $KHSO_5$ at pH 7.7, $\mu = 0.20$ mol dm^{-3}, 30°C. OMn(IV)T2MPyP (– – –), Mn(III)T2MPyP (————).

immediately leads to the complete generation of the oxomanganese(IV) porphyrin (Soret band at λ_{max} 424 nm) (Fig. 2).

The OMn(IV)T2MPyP species was relatively short-lived and decayed back to Mn(III)T2MPyP (λ_{max} 454 nm) within a few minutes. A brief study of the pH dependence of the stability of OMn(IV)T2MPyP in the pH range 5.7–8.1 showed that increasing pH leads to increasing stability (Table 1). To allow direct comparison with our previous study, using OFe(IV)T2MPyP, pH 7.7 was selected for the kinetic studies.

With the reactant concentrations which were subsequently used for the kinetic study (6.0×10^{-6} mol dm^{-3} Mn(III)T2MPyP with 3.0×10^{-6} mol dm^{-3} $KHSO_5$, porphyrin:oxidant molar ratio of 2:1) the first half-life of the oxomanganese species was 48 seconds and the reaction led to approximately 5% bleaching of the regenerated Mn(III) porphyrin concentration.

The fact that OMn(IV)T2MPyP has a short half-life at pH 7.7 caused problems with the handling of this species, since it was not easy to generate the high-valent species by reacting Mn(III)T2MPyP with $KHSO_5$ prior to reacting it with phenolic substrates, in the way described by Colclough and Lindsay Smith for OFe(IV)T2MPyP [8]. Consequently in this study a method used by Vidal et al. was adopted which involves generating the OMn(IV) porphyrin species in situ in the presence of the phenolic substrate [9].

2.2. *The reaction of OMn(IV)T2MPyP with a selection of substrates in aqueous solution*

In order to investigate the capability of OMn(IV)T2MPyP to carry out oxidations, these substrates were chosen, pyridine, dimethyl sulphoxide, triethylphosphite and 4-fluorophenol. The reactivity of

Table 1
pH dependence of the stability of OMn(IV)T2MPyP generated from Mn(III)T2MPyP (6.0×10^{-6} mol dm^{-3}) and $KHSO_5$ (2.4×10^{-5} mol dm^{-3}) at pH 7.7, $\mu = 0.20$ mol dm^{-3}, 30°C

pH	Half-life of OMn(IV)T2MPyP (s)
5.7	20
6.4	75
7.7	180
8.1	287

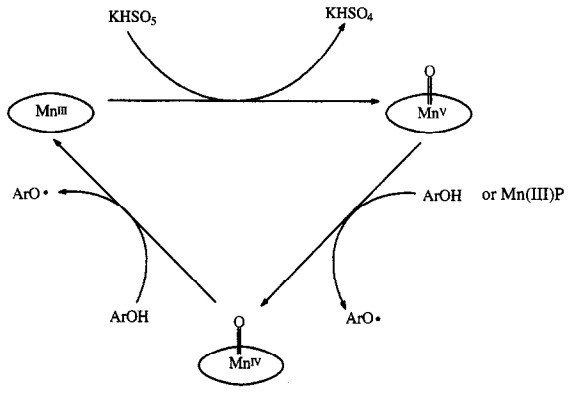


Fig. 3. The peroxidase-type reaction cycle for oxidation of phenols by oxomanganese species generated by the in situ reaction of Mn(III)T2MPyP and $KHSO_5$.

these compounds was determined by comparison of the rate of decay of OMn(IV)T2MPyP in the absence of a substrate with that in the presence of a substrate. Only 4-fluorophenol was found to be reactive towards OMn(IV)T2MPyP.

2.3. Kinetic studies of the reaction of OMn(IV)T2MPyP with phenols in aqueous solution

The method developed by Colclough and Lindsay Smith [8] involved preforming the OFe(IV)T2MPyP species and than reacting it with the phenol substrate using a stopped flow apparatus. When applied to the analogous manganese porphyrin, the rate of reaction of OMn(IV)T2MPyP, which had been generated by addition of $KHSO_5$ to Mn(III)T2MPyP was monitored by the reappearance of the 454 nm λ_{max} absorbance of the manganese(III) porphyrin.

Using the method by Vidal et al. [9], a buffered solution of Mn(III)T2MPyP and the phenol was mixed with a solution of $KHSO_5$ in the same buffer in a cuvette using a stopped-flow apparatus. It is assumed that this produced OMn(V)T2MPyP initially which reacted with the excess of the phenolic substrate present to give the OMn(IV)T2MPyP. The conversion of OMn(V)T2MPyP to OMn(IV)T2MPyP took place so fast that it was not possible to detect the former species by UV–Vis spectroscopy. The kinetics of the slower reactions of OMn(IV)T2MPyP with the phenols, which were followed by measuring the reappearance of Mn(III)T2MPyP (λ_{max} 454 nm), were started 0.1 s after the mixing of the reactants and monitored at 0.1 s time intervals. The overall peroxidase-like reaction cycle is shown in Fig. 3.

Table 2
k_{obs} (pseudo first order rate constant) values obtained from the two different methods of investigation for the reaction of OMn(IV)T2MPyP [generated from Mn(III)T2MPyP (6.0×10^{-6} mol dm^{-3}) with $KHSO_5$ (3.0×10^{-6} mol dm^{-3})] with 4-fluorophenol (6.0×10^{-4} mol dm^{-3}) at pH 7.7, 30°C, $\mu = 0.20$ mol dm^{-3}

Method	
OMn(IV)T2MPyP preformed k_{obs} /s	OMn(IV)T2MPyP formed in situ k_{obs} /s
3.25	3.13
3.16	3.28
3.22	3.27
3.35	3.21

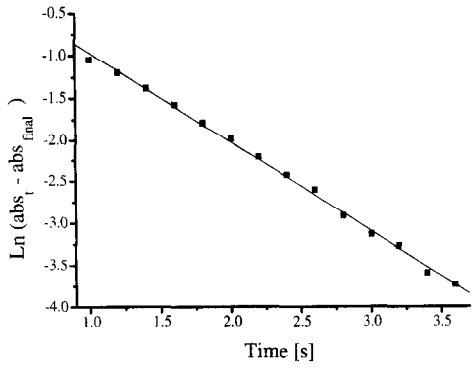


Fig. 4. Plot of the integrated first-order rate equation for reduction of OMn(IV)T2MPyP (from Mn(III)T2MPyP 6.0×10^{-6} mol dm^{-3} and $KHSO_5$ 3.0×10^{-3} mol dm^{-3}) by 4-fluorophenol (1.85×10^{-4} mol dm^{-3}), pH 7.7, $\mu = 0.20$ mol dm^{-3} at 30°C obtained with the in situ method.

Both methods were examined under identical reaction conditions and gave the same pseudo first order rate constant, k_{obs}, for the reaction of 4-fluorophenol with OMn(IV)T2MPyP (Table 2). This led to the conclusion that the initial rapid formation of OMn(V)T2MPyP and reduction to OMn(IV)T2MPyP using the in situ method did not interfere with the measured reaction kinetics between the phenol substrate and the OMn(IV)T2MPyP. Since, however, this method allowed a much easier experimental handling of the high-valent oxomanganese species it was used in all further studies.

2.4. Defining the kinetic equation

All the rates of reduction of OMn(IV)T2MPyP to Mn(III)T2MPyP by the phenols [16.3–95.0 excess over Mn(III)T2MPyP] were found to fit first-order kinetics for more than 3 half-lives (see for example Fig. 4). The pseudo-first order rate constant, k_{obs}, for each phenol concentration was obtained as an average value from 10–12 reactions, where the scatter of values was small, for example, k_{obs} for 1.45×10^{-4} mol dm^{-3} 4-fluorophenol was found to be 0.85 ± 0.04 s^{-1}, with the error representing 95% confidence limits. The plots of k_{obs} vs. the phenol concentrations (corrected for the extent of ionisation) gave good linear dependencies of the rate constants on the concentration

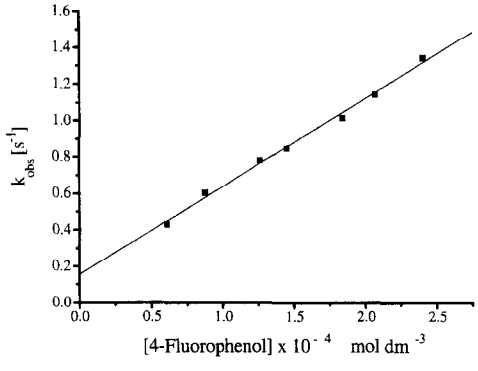


Fig. 5. Dependence of the pseudo-first order rate constant, k_{obs}, for the reduction of OMn(IV)T2MPyP by 4-fluorophenol on [4-fluorophenol], pH = 7.7, $\mu = 0.20$ mol dm^{-3} at 30°C.

Table 3
The independence of k_{obs} on OMn(IV)T2MPyP concentration at pH 7.7, $\mu = 0.20$ mol dm^{-3}, 30°C. 4-fluorophenol (1.85×10^{-4} mol dm^{-3}), OMn(IV)T2MPyP formed in all cases by addition of half an equivalent of $KHSO_5$ relative to Mn(III)T2MPyP

Concentration of Mn(III)T2MPyP used to generate OMn(IV)T2MPyP with $KHSO_5$ /10^{-5} mol dm^{-3}	k_{obs} /s
1.5	1.15
1.2	1.11
0.9	1.06
0.6	1.12
0.3	1.09

of each phenol (Fig. 5). The independence of k_{obs} on [OMn(IV)T2MPyP] was confirmed using a constant concentration of 4-fluorophenol and a range of oxomanganese concentrations (Table 3).

The results above show that the reactions obey the kinetic equation, (A)

$$\frac{-d[OMn(IV)T2MPyP]}{dt} = k_{obs}[OMn(IV)T2MPyP] \qquad (A)$$

$$k_{obs} = k_2[ArOH]$$

The second-order rate constant, k_2, for each phenol, was obtained from the gradient of the linear k_{obs} versus phenol concentration plots, e.g. k_2 for 4-fluorophenol was determined as 0.48×10^4 dm^3 mol^{-1} s^{-1} from the gradient of Fig. 5. Table 4 shows the k_2 values for each of the phenols investigated in this study.

3. Discussion

3.1. Attempts to generate OMn(IV)T2MPyP from Mn(III)T2MPyP with t-BuO_2H, magnesium monoperphthalate and H_2O_2

Initially we attempted to generate OMn(IV)T2MPyP from Mn(III)T2MPyP using t-BuO_2H which had proved an effective oxidant for the analogous iron system. However, this did not lead to a good

Table 4
Second-order rate constants for the reaction of OMn(IV)T2MPyP with phenols in aqueous solution. OMn(IV)T2MPyP [prepared from Mn(III)T2MPyP (6.0×10^{-6} mol dm^{-3}) and $KHSO_5$ (3.0×10^{-6} mol dm^{-3})], phosphate buffer (0.05 mol dm^{-3}), pH = 7.7, $\mu = 0.20$ mol dm^{-3}, 30°C

Phenol substrate XC_6H_4OH; X =	Phenol concentration range/10^{-4} mol dm^{-3}	k_2 [a] /10^4 dm^3 mol^{-1} s^{-1}
3-CN	0.58–2.14	0.12 ± 0.03
3-F	0.48–2.76	0.40 ± 0.16
H	0.56–2.44	0.42 ± 0.09
4-F	0.61–2.41	0.48 ± 0.06
4-Cl	0.61–2.47	0.68 ± 0.11
4-Me	0.65–2.40	1.03 ± 0.21
4-OMe [b]	0.32–1.26	1.50 ± 0.25

[a] Errors in k_2 calculated to give 95% confidence limits for linear fits of k_{obs} vs. [ArOH].
[b] OMn(IV)T2MPyP generated from Mn(III)T2MPyP (3.0×10^{-6} mol dm^{-3}) and $KHSO_5$ (1.5×10^{-6} mol dm^{-3}).

conversion to the oxomanganese(IV) porphyrin. Replacing t-BuO_2H with either H_2O_2 or magnesium monoperphthalate and increasing the oxidant to porphyrin ratio from 1:1 to 150:1 did not overcome this problem. We argued that the oxomanganese(IV) porphyrin was reverting to Mn(III)T2MPyP by reacting with the oxidants [see for example Reaction (1)] so that in effect the porphyrin was catalyzing the decomposition of the oxidant and a steady state concentration of OMn(IV)T2MPyP was being observed. In agreement with this conclusion the more powerful oxidant, $KHSO_5$, led to the rapid and quantitative conversion of Mn(III)T2MPyP to OMn(IV)T2MPyP.

(1)

3.2. Decay of OFe(IV)T2MPyP and OMn(IV)T2MPyP without substrates in aqueous solution at pH 7.7

A striking difference in the behaviour of OMn(IV)T2MPyP and OFe(IV)T2MPyP is their stability in the absence of an oxidizable substrate in aqueous solution at pH 7.7. The first half-life of the iron species is approximately 10 h [8] whereas that of OMn(IV)T2MPyP is 48 s. The stability of the latter, as has been noted previously for the isomeric OMn(IV)T4MPyP [10], decreases with the pH of the solution.

Spreer et al. [10] carried out an extensive study of the reduction of OMn(IV)T4MPyP to the Mn(III) porphyrin in aqueous solution in the absence of oxidizable substrates. They concluded that at high pH the Mn(IV) species exists as a manganese(IV)–manganese(IV) μ-oxodimer and that the generation of the Mn(III) porphyrin involves the conversion of a small proportion of this dimer into manganese(IV)–manganese(III) μ-oxodimer π radical cation. Nucleophilic attack on the porphyrin ring of the radical cation gives an oxygenated manganese(III) porphyrin which subsequently provides multiple electrons for the reduction of further OMn(IV) species. In this way 4–8% of the manganese porphyrin is extensively degraded and provides the electrons to reduce the remainder of OMn(IV)T4MPyP.

Under more acidic conditions the μ-oxodimers break up to monomeric species and the Mn(III) porphyrin π radical cation is favoured over the manganese(IV) species [11]. This increase in manganese(III) porphyrin π radical cation could account for the shorter life-time of OMn(IV)T4MPyP in acidic solution.

In the present study at pH 7.7, using tetra(2-*N*-methylpyridyl)porphyrin, which has a lower tendency to dimerize than the 4-isomer, the OMn(IV)T2MPyP species are likely to be monomeric. However, it is probable that the mechanism proposed by Spreer et al. for the μ-oxodimer of

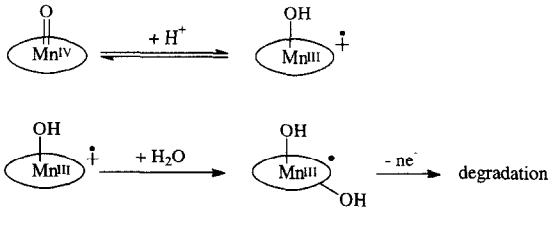


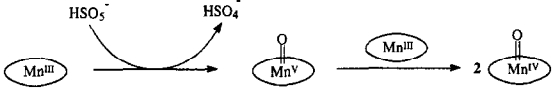
Fig. 6. Porphyrin degradation due to nucleophilic attack of a solvent molecule on the Mn(III)T2MPyP π radical cation species.

Mn(IV)T4MPyP also applies for the monomeric OMn(IV)T2MPyP (Fig. 6). The observed loss of $\approx 5\%$ of the manganese T2MPyP in the self oxidation agrees with this conclusion and with the observations of Spreer et al.

The slower rate of self reaction of OFe(IV)T2MPyP than OMn(IV)T2MPyP suggests that either this mechanism does not apply to the oxoiron(IV) species or, more probably, electron rearrangement in the oxoiron(IV) porphyrin to give iron(III) porphyrin π radical cation is less favoured and, consequently, subsequent reactions of this species occur more slowly.

3.3. Generation of OMn(IV)T2MPyP from Mn(III)T2MPyP with $KHSO_5$

As described previously, it was considered important in this kinetic study to avoid an excess of oxidant to prevent the recycling of any Mn(III)T2MPyP formed as a product from the reaction of the OMn(IV) porphyrin with the phenol substrate (Fig. 3), since this would introduce unnecessary complications to the kinetic measurements. For this reason a half equivalent of the oxidizing agent relative to Mn(III)T2MPyP was used: $KHSO_5$ produces two oxidizing equivalents and, in the absence of a substrate, one mol of $KHSO_5$ should lead to the formation of two mol of OMn(IV)T2MPyP (Reaction 2).



(2)

In the presence of a phenol substrate the amount of OMn(IV)T2MPyP obtained will be less than that in its absence because the initially formed OMn(V)T2MPyP can be rapidly reduced to the oxomanganese(IV) species by both Mn(III)T2MPyP and the phenol (Fig. 3). Since the phenol is present in large excess over the manganese porphyrin the latter reaction is likely to predominate. Assuming the half equivalent of $KHSO_5$ oxidizes half of the Mn(III)T2MPyP to OMn(V)T2MPyP and all of the latter is then reduced by the phenol to OMn(IV)T2MPyP, the overall molar conversion of manganese(III) to oxomanganese(IV) by $KHSO_5$ will be 50%. As a consequence of this initial reaction, prior to the kinetic measurements, the absolute concentration of the phenol should be corrected. However, the adjustment is very small and calculations show that using the corrected phenol concentrations in k_{obs} vs concentration plots leads to insignificant changes in k_2 values (the gradient of the plot).

The conclusions, from these calculations and from the fact that the k_{obs} values are independent of the method which is used to generate OMn(IV)T2MPyP (Table 2), are that the observed kinetics of the reaction are not affected by whether the OMn(IV)T2MPyP is generated in situ with the phenol substrate present or is prepared prior to the introduction of the phenol to the system.

3.4. Mechanistic analysis of the oxidation of phenols by oxomanganese(IV) tetra(2-N-methylpyridyl)porphyrin

OMn(IV)T2MPyP does not react with pyridine, dimethylsulphoxide or triethylphosphite, substrates which should be reactive towards electrophilic oxygen transfer, although it does react with phenols and analogous oxomanganese(IV) species are known to oxidize alkenes both in protic and aprotic solvent [7]. These results can be rationalized as oxomanganese(IV) porphyrin active oxidants

Table 5
Log k_2 values for the oxidation of phenols by OMn(IV)T2MPyP, pK_a values of phenols and the σ, $\sigma^{\cdot}$ and σ^+ values of the substituents

Phenol substrate XC_6H_4OH; X =	log k_2 [a]	pK_a of phenol [b]	σ [*] [c]	σ^+ [*] [d]	$\sigma^{\cdot}$ [*] [e]
3-CN	3.08	8.6	0.56	0.56	−0.026
3-F	3.60	9.2	0.34	0.34	− 0.009
H	3.62	10.0	0	0	0
4-F	3.68	9.9	0.06	−0.07	−0.011
4-Cl	3.83	9.4	0.23	0.11	0.011
4-Me	4.01	10.3	−0.17	−0.31	0.015
4-OMe	4.17	10.1	−0.27	−0.78	0.018

[a] k_2 values from Table 4.
[b] pK_a values from [12].
[c] σ values from McDaniel and Brown [13].
[d] σ^+ values for para substituents from Brown and Okamoto [14].
[e] $\sigma^{\cdot}$ values from Arnold and coworkers [15].

behaving as oxyradicals [7]. Such species would be expected to epoxidize and oxidize alkenes and to react with phenols by either hydrogen atom abstraction or electron transfer [Reactions (3) and (4)].

$$\text{OMn(IV)P} + \text{ArOH} \underset{+\text{H}^+}{\overset{-\text{e}^-}{\rightarrow}} \text{ArOH}^{+\cdot} + \text{HOMn(III)P} \overset{-\text{H}^+}{\rightarrow} \text{ArO}^{\cdot} \quad (3)$$

$$\text{OMn(IV)P} + \text{ArOH} \rightarrow \text{ArO}^{\cdot} + \text{HOMn(III)P} \quad (4)$$

In our previous study of the oxidation of phenols by OFe(IV)T2MPyP, the iron analogue of OMn(IV)T2MPyP, we showed that the phenols and not their anions are the substrates. Furthermore by using a Hammett analysis, we found that the rate determining step in these reactions involve a homolytic hydrogen atom abstraction by the oxoiron species with a small degree of charge separation in the transition state [8]. The present kinetic study was initiated to compare the activity and oxidation mechanisms of the oxoiron(IV) and oxomanganese(IV) porphyrin species. The reactions in the present study were carried out at pH 7.7 to allow direct comparison with our earlier study and to ensure that the phenols were predominantly unionized under the reaction conditions (pK_a values in Table 5).

To determine whether OMn(IV)T2MPyP reacts with phenols by electron or hydrogen atom transfer (Reactions 3 and 4), Hammett and modified Hammett analyses of the second order rate constants, k_2, were undertaken (Table 6).

The plot of log k_2 vs. σ values gives a straight line with a relatively poor correlation coefficient (0.888) and a p value of -1.06. Repeating the plot with σ^+ values shows little improvement in the correlation coefficient (0.900) and leads to a ρ value of -0.72. However, a significant improvement is achieved using $\sigma^{\cdot}$ values which give a linear plot with a correlation coefficient of 0.944 and a ρ

Table 6
ρ values of the Hammett analyses of the reaction of OFe(IV)T2MPyP and OMn(IV)T2MPyP with phenols at pH 7.7

	Oxometalloporphyrin species			
	OFe(IV)T2MPyP [a] ρ	Correlation coefficient	OMn(IV)T2MPyP ρ	Correlation coefficient
σ	−1.52	0.881	−1.06	0.888
σ^+	−1.10	0.956	−0.72	0.900
$\sigma^{\cdot}$	18.80	0.920	21.35	0.944
$\sigma^+ + \sigma^{\cdot}$ [b]	10.00 [b]	0.972	46.80 [b]	0.968

[a] Ref. [8].
[b] Ratio $\rho^{\cdot}/\rho^+$ from the dual parameter Hammett equation (Eq. B).

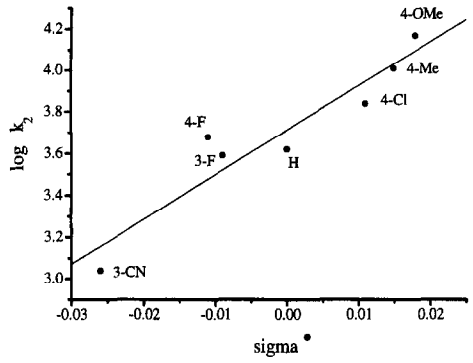


Fig. 7. Correlation of log k_2 versus $\sigma^{\cdot}$ for phenol oxidation by OMn(IV)T2MPyP, conditions as given in Fig. 4.

value of 21.35 (Fig. 7). The $\sigma^{\cdot}$ values were those of Arnold and Dust, obtained from substituent effects on the hyperfine coupling constants in the EPR spectra of benzyl radicals. Bearing in mind the similar structures of benzyl and phenoxyl radicals, rates of reaction that involve the formation of phenoxyl radicals might be expected to correlate well with $\sigma^{\cdot}$ values obtained in this way [15]. It should, however, be noted that since radical stabilizing effects of substituents are small compared with their charge stabilizing effects on ions, $\sigma^{\cdot}$ correlations are commonly only observed in reactions where charge development is small or unimportant.

The poor correlation of $\log k_2$ with σ and σ^+ [cf. the comparable values for oxoiron porphyrin (Table 6)] suggests that there is little charge development or destruction in the rate determining transition state of the reaction. Furthermore, taken in conjunction with the relatively small ρ values obtained from these poor correlations this suggests a hydrogen atom abstraction rather than an electron-transfer mechanism. The latter involves the generation of a radical cation, (reaction 3), and would be expected to have a significantly larger value. As described previously [16], typical electron transfer reactions, e.g. the reaction of $Pb(OAc)_4$ with $ArNMe_2$ have ρ values of approximately -2 to -3 and correlate best with σ^+, whereas the known hydrogen atom abstractions from phenols have values of about -1.0. In agreement with this conclusion, the reasonable correlation of the $\log k_2$ values with $\sigma^{\cdot}$ indicates significant radical character in the transition state of the reaction between phenols and OMn(IV)T2MPyP.

In an attempt to quantify the dominance of the radical over the polar character in the transition state of the phenol/OMn(IV)T2MPyP reaction, the dual parameter Hammett analysis [equation B], which

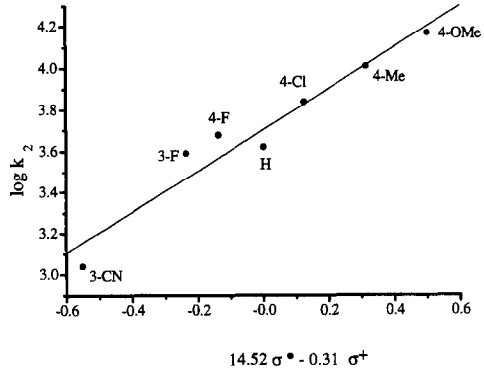


Fig. 8. Correlation of log k_2 versus $\sigma^{\cdot} + \sigma^+$ for phenol oxidations by OMn(IV)T2MPyP, conditions as given in Fig. 4.

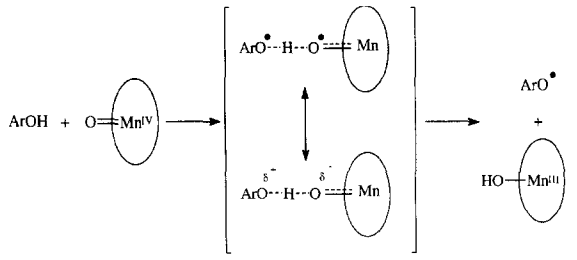


Fig. 9. Proposed hydrogen atom abstraction mechanism for the oxidation of phenols by OMn(IV)T2MPyP at pH 7.7.

was developed by Arnold and coworkers, was applied to the rate data. This gives a good correlation coefficient of 0.968, with ρ and $\rho^{\cdot}$ values of -0.31 and 14.5, respectively (Fig. 8). The ratio of $\rho^{\cdot}/\rho$ which is a measure of the relative importance of radical and polar effects in the transition state is 46.8 [cf. the value for phenol oxidation by OFe(IV)T2MPyP is 10.0]. When this value is compared with those from other hydrogen abstraction reactions, the dominant radical character in the transition state is evident. Indeed the ratio is considerably higher than that from C–H hydroxylation of $ArCHMe_2$ by the Fe(III)TPP/PhIO system which is generally considered to arise via hydrogen atom abstraction by $OFe(IV)TPP^{+\cdot}$ in an oxygen rebound mechanism [17]. The application of the dual parameter equation to the results from the present study leads to a significantly improved linear correlation of the data compared to the single parameter $\log k_2$ vs. $\sigma^{\cdot}$ plot. Based on this observation and the large value of $\rho^{\cdot}/\rho$, we conclude that the mechanism of phenol oxidation by OMn(IV)T2MPyP is the same as that we proposed for the analogous reaction of OFe(IV)T2MPyP [8] and involves hydrogen atom abstraction from the phenol (Fig. 9). Both the oxometal(IV) porphyrins behave as electrophilic radicals which show some charge separation in the transition states of their reactions with phenols.

$$\log(k_X/k_H) = \rho\sigma^{+} + \rho^{\cdot}\sigma^{\cdot} \qquad \text{(B)}$$

3.5. Rate of reaction of OFe(IV)T2MPyP and OMn(IV)T2MPyP with phenol substrates at pH 7.7

The second order rate constants for phenol oxidations for both oxometal porphyrin species are very comparable with those of OFe(IV)T2MPyP being larger. Since the reaction conditions for oxidations

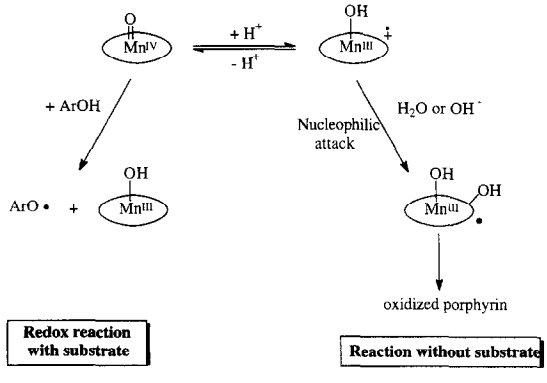


Fig. 10. Reaction pathways for OMn(IV)T2MPyP in the presence of a phenol substrate (redox reaction) and for $Mn(III)T2MPyP^{+\cdot}$ in the absence of a phenol substrate (autodegradation).

by both species were identical (temperature, buffer, ionic strength and pH), the differences in the rates of the reactions must arise from the different metal in the oxometalloporphyrin.

The fact, that the half-life of OMn(IV)T2MPyP at pH 7.7 in the absence of substrate is shorter than that of OFe(IV)T2MPyP whereas its reaction with the phenols is slower than that of the iron(IV) analogue indicates that the two reductions of the OMn(IV)T2MPyP, in the presence and absence of phenol probably occur by different mechanisms. Assuming an equilibrium of the OMn(IV) porphyrin species and the Mn(III) porphyrin–radical cation is present at pH 7.7 [10], we suggest it is possible that each species is responsible for one reaction pathway; thus OMn(IV)T2MPyP may react with the phenol, whereas as discussed above the Mn(III) porphyrin–radical cation is involved in the regeneration of the manganese(III) porphyrin in the absence of the phenol (Fig. 10).

4. Experimental

4.1. Materials

Commercially available materials were purchased from Aldrich Chemical Co. Ltd. and used without further purification. Phenol was purified by vacuum distillation and stored under nitrogen in containers excluding light. Potassium monopersulphate was 38.67% by weight and regularly checked during the course of this research by iodometric titration. Deionized water was used throughout the study.

4.1.1. Preparation of 5,10,15,20-tetra(2-pyridyl)porphyrin [18,19]

Equimolar quantities of freshly distilled pyrrole (3.35 g, 0.05 mol) and pyridine-2-carboxaldehyde (5.35 g, 0.05 mol) were simultaneously and slowly added to 0.6 dm^3 of stirred acetic acid at 90°C. After six hours, the solvent was removed by distillation to leave a crystalline residue with a purple hue which was dissolved in the minimum amount of trichloromethane and purified by flash chromatography on a silica column (35 × 4 cm, 230–400 mesh). Approximately 3 dm^3 of trichloromethane was used to elute all the impurities before the solvent was changed to a mixture of trichloromethane and methanol, initially with 1% methanol (0.5 dm^3), then 2% (0.5 dm^3) and finally 5% methanol (0.5 dm^3). The dark red solution obtained with the 2% methanol mixture contained the desired porphyrin. Removal of the solvent under vacuum gave 2.08 g (26.9%) yield. TLC analysis (on silica, trichloromethane:methanol = 98:2, $R_f = 0.44$), ^{1}H-NMR and EI-MS spectroscopy showed this material to be pure and essentially free of the corresponding chlorin.

^{1}H-NMR: (300 MHz, $CDCl_3$) δ [ppm] 9.14 (ddd, 4H, $^3J_{34} = 4.91$ Hz, $^4J_{35} = 1.77$ Hz, $^5J_{36} = 1.05$, 3-pyridyl); 8.86 (s, 8H, β-pyrrole); 8.21 (m, 4H, $^3J_{56} = 7.62$ Hz, $^4J_{46}$ = undetermined, $^5J_{36}$ = undetermined, 6-pyridyl); 8.09 (ddd, 4H, $^3J_{56} = 7.62$ Hz, $^3J_{45} = 7.55$ Hz, $^4J_{35} = 1.77$ Hz, 5-pyridyl); 7.71 (ddd, 4H, $^3J_{45} = 7.55$ Hz, $^3J_{34} = 4.91$ Hz, $^4J_{46} = 1.20$ Hz, 4-pyridyl); −2.82 (s, 2H, pyrrole NH); EI-MS: $m/z = 618$ [M^+], calc. 618.70; UV–Vis: λ (nm) (log ε, ε [mol^{-1} dm^3 cm^{-1}]) in 1.0 M HCl: 435 (5.32), 584 (4.04), 632 (3.90).

4.1.2. Preparation of 5,10,15,20-tetra(2-N-methylpyridyl)porphyrin [20–22]

5,10,15,20-Tetra(2-pyridyl)porphyrin (0.962 g, 1.55×10^{-3} mol) was dissolved in DMF (0.15 dm^3), heated to reflux and methyl *p*-toluenesulphonate (11.58 g, 0.062 mol) was rapidly added. After 8 h at refluxing temperature, the solvent was removed by high-vacuum distillation to leave a black

slurry which was dissolved in water (ca. 0.2 dm^3) and extracted with diethyl ether to remove the excess of the methylating agent (3×50 cm^3). A saturated solution of ammonium hexafluorophosphate in water was added to the mixture which was then stirred for ca. 20 min before the precipitate was removed by filtration, carefully washed with water to remove excess of $NH_4^+PF_6^-$ and dissolved in a small amount of water/acetonitrile (1:10, 30 cm^3 total volume). The counter anion was converted to chloride by stirring the solution for ca. 30 min with Amberlite CG 400 anion exchange resin, Cl^- form (23.89 g, $20 \times$ excess). It is very important that the ion exchange resin is thoroughly washed with water before it is used in order to remove impurities in the commercial resin. The used exchange resin was removed by filtration and the solution was eluted with water through a short column of the same resin to ensure the exchange was complete. Finally the water was removed in vacuo to leave 1.22 g (82% yield) of the desired *N*-methylated porphyrin as a purple shining residue.

FAB-MS of the PF_6^- porphyrin salt: $m/z = 1113$ ($M^+ + 3PF_6^-$, calc. 1113.73), 968 ($M^+ + 2PF_6^-$, calc. 968.77), 823 ($M^+ + 1PF_6^-$, calc. 823.80), 808 ($M^+ - CH_3, + PF_6^-$, calc. 808.77); UV–Vis (λ [nm] (log, [mol^{-1} dm^3 cm^{-1}]) in 1.0 M HCl: 412 (5.49), 513 (4.19), 544 (3.57), 581 (3.86), 633 (3.13); Anal. Found: C 56.69; N 11.87; H 5.21 $C_{44}H_{38}N_8(Cl)_4(H_2O)_6$ requires C 56.90; N 12.07; H 5.43

4.1.3. Preparation of manganese(III) 5,10,15,20-tetra(2-N-methylpyridyl)porphyrin [23]

Manganese metal powder (5.96 g) was added to 5,10,15,20-tetra(2-*N*-methylpyridyl)porphyrin (0.596 g, 6.42×10^{-4} mol) dissolved in water (ca. 0.8 dm^3). The mixture was heated to reflux and held at this temperature for 1–2 h before the excess Mn was separated by filtration and the solvent removed in vacuo. The purification of the product involved, first recrystallisation from acetonitrile/methanol (20:1), secondly precipitation from water with ammonium hexafluorophosphate to give the metallated porphyrin–PF_6^- salt and finally ion exchange to convert the counter ion to Cl^- with Amberlite CG 400 anion exchange resin, Cl^- form (15.97 g). After the removal of the solvent the product was obtained as a black, metallic shining residue (0.62 g, 95% yield).

FAB-MS of the PF_6^- porphyrin salt: $m/z = 1311$ ($M^+ + 4PF_6^-$, calc. 1311.62), 1166 ($M^+ + 3PF_6^-$, calc. 1166.65), 1021 ($M^+ + 2PF_6^-$, calc. 1021.69); UV–Vis: λ [nm] ($\log\varepsilon$, ε [10^3 mol^{-1} dm^3 cm^{-1}]) in H_2O: 364 (4.66), 454 (4.97), 554 (4.12); Anal. Found: C 51.33; N 10.47; H 4.42 $MnC_{44}H_{36}N_8(Cl)_5(H_2O)_7$ requires C 51.05; N 10.83; H 4.87

4.2. Methods

UV–Vis spectra and kinetic data were recorded on a Hewlett Packard 8452A diode array spectrometer. The data were stored and analyzed on a Hewlett Packard HP9500 UV–Vis Chemstation with a kinetics software package 89512A. For the study of rapid reactions a Photophysics RX 1000 stopped-flow apparatus equipped with 2.5 cm^3 drive syringes and a dual pathlength (10/2 mm) cuvette was attached to the spectrometer. The syringes and the reaction chamber were thermostatted at 30°C. pH Measurements were made with a Corning pH meter 220 equipped with a Reagecom combined pH/reference electrode.

Mass spectra were recorded on a VG Analytical Autospec instrument. For tetra(2-pyridyl)porphyrin, fragments were generated by electron impact (EI). For all other porphyrins, the instrument was used in FAB^+ mode with a NOBA matrix.

^1H NMR spectra were recorded on a Bruker MSL 300 spectrometer (300 MHz) using D_2O and $CDCl_3$ solvents with DSS and TMS as references respectively.

The Hammett treatment of the rate data was carried out on a Lion personal computer equipped with a least mean square linear regression programme. Dual parameter Hammett analysis of the rate data was achieved using a multiple regression function of the programme above.

4.3. Kinetic procedures

4.3.1. Generation of OMn(IV)T2MPyP prior to kinetic studies

One drive syringe of the stopped-flow apparatus was loaded with a buffered phenol solution and the other with OMn(IV)T2MPyP, generated by addition of $KHSO_5$ to a buffered solution of Mn(III)T2MPyP and $NaNO_3$ (the final ionic strength of the mixture was 0.20 mol dm^{-3}). Following the rapid mixing of equal volumes of the solutions from the two drive syringes in the cuvette, the reappearance of Mn(III)T2MPyP (454 nm λ_{max}) was monitored. The total volume of each reaction was 0.3 cm^3 which allowed 10–12 kinetic runs to be recorded for each pair of solutions reacted. In the kinetic analysis the data from these runs were averaged.

4.3.2. Reaction of OMn(IV)T2MPyP with non-phenolic substrates

Mn(III)T2MPyP (1.2×10^{-5} mol dm^{-3}) was mixed in a UV-cell with (i) pyridine, (ii) dimethyl sulphoxide and (iii) triethylphosphite (1.2×10^{-4} mol dm^{-3}) at 30°C. Then $KHSO_5$ (7.2×10^{-5} mol dm^{-3}) was added and the reappearance of the 454 nm λ_{max} absorbance of the manganese(III) porphyrin was monitored. To establish the reactivity of OMn(IV)T2MPyP towards these substrates the rate of decay of OMn(IV)T2MPyP to Mn(III)T2MPyP in the absence of a substrate was compared to the rate under identical conditions with a substrate present in the reaction mixture.

4.3.3. In situ generation of OMn(IV)T2MPyP

In a typical reaction one of the drive syringes was filled with a buffered solution of potassium monopersulphate whilst the second drive syringe was filled with a buffered solution of Mn(III)T2MPyP, $NaNO_3$ (to hold the ionic strength of the reaction mixture at 0.2 mol dm^{-3}) and the phenol substrate. The reaction was followed as described above by monitoring the reappearance of Mn(III)T2MPyP after rapid mixing of equal volumes of the two solutions. The volume of the solutions in the drive syringes was sufficient for approximately 10 to 12 kinetic runs and in the kinetic analysis the data from these runs were averaged.

References

[1] (a) P.R. Ortiz de Montellano (Ed.), Cytochrome P450: Structure, Mechanism and Biochemistry, Plenum, New York, 1986; (b) H.B. Dunford, in J. Everse, K.E. Everse and M.B. Grisham (Ed.), Peroxidases in Chemistry and Biology, Vol. 2, CRC Press, Boca Raton, FL, 1991, p. 1; (c) P.R. Ortiz de Montellano, Ann. Rev. Pharmacol. Toxicol., 32 (1992) 89.

[2] (a) B. Meunier, Chem. Rev., 92 (1992) 1411; (b) F. Montanari and L. Casella (Ed.), Metalloporphyrin Catalysed Oxidations, Kluwer, Dordrecht, 1994; (c) R.A. Sheldon (Ed.) Metalloporphyrins in Catalytic Oxidations, Marcel Dekker, New York, 1994.

[3] M.H. Gelb, W.A. Toscano and S.G. Sligar, Proc. Natl. Acad. Sci. USA, 79 (1982) 5758.

[4] (a) R. Makino, T. Uno, Y. Nishimura, T. Iizuka, M. Tsuboi and Y. Ishimura, J. Biol. Chem., 261 (1986) 8376; (b) H. Hori, M. Ikeda and T. Yonetani, Biochim. Biophys. Acta, 912 (1987) 74; (c) R.J. Nick, G.B. Ray, K.M. Fish, T.G. Spiro and T.J. Groves, J. Am. Chem. Soc., 113 (1991) 1838.

[5] (a) C.L. Hill and B.C. Schardt, J. Am. Chem. Soc. 102 (1980) 6374; (b) J.T. Groves, W.J. Kruper and R.C. Haushalter, J. Am. Chem. Soc., 102 (1980) 6375; (c) E. Guilmet and B. Meunier, Tetrahedron Lett., (1980) 4449; (d) S. Campestrini and B. Meunier, Inorg. Chem., 31, (1992) 1999; (e) J.P. Collman, X. Zhang, R.T. Hembre and J.I. Brauman, J. Am. Chem. Soc., 112 (1992) 5325; (f) F. Montanari, S. Banfi, G. Pozzi and S. Quici, in F. Montanari and L. Casella (Ed.), Metalloporphyrin Catalysed Oxidations, Kluwer, Dordrecht, 1994, p. 149.

[6] (a) I. Tabushi and N. Koga, J. Am. Chem. Soc., 101 (1979) 6456; (b) D. Mansuy, M. Fontecave and J.F. Bartoli, J. Chem. Soc. Chem. Commun., (1983) 253; (c) E.I. Karasevich, A.M. Khenkin and A.E. Shilov, J. Chem. Soc., Chem. Commun., (1987) 731; (d) P. Battioni, J.F. Bartoli, P. Leduc, M. Fontecave and D. Mansuy, J. Chem. Soc. Chem. Commun., (1987) 791; (e) P. Battioni, J.P. Renaud, J.F. Bartoli, M. Reina-Artilles, M. Fort and D. Mansuy, J. Am. Chem. Soc., 110 (1988) 8462; (f) A.E. Shilov and E.I. Karasevich, in F. Montanari and L. Casella (Ed.), Metalloporphyrin Catalysed Oxidations, Kluwer, Dordrecht, 1994, p. 87.
[7] (a) J.T. Groves and M.K. Stern, J. Am. Chem. Soc., 109 (1987) 3821; (b) R.D. Arasasingham, G. He, T.C. Bruice, J. Am. Chem. Soc. 115 (1993) 7985.
[8] N. Colclough and J.R. Lindsay Smith, J. Chem. Soc. Perkin Trans. 2, (1994) 1139.
[9] M. Vidal, M. Bonnafous; S. Defrance, P. Loiseau, J. Bernadou and B. Meunier, Drug Metab. Dispos. 21 (1993) 811.
[10] L.O. Spreer, A. Leone, A.C. Maliyackel, J.W. Otvos and M. Calvin, Inorg. Chem. 27 (1988) 2401.
[11] N. Carnieri, A. Harriman and G. Porter, J. Chem. Soc., Dalton Trans., (1982) 931.
[12] E.P. Serjeant and B. Dempsey, Ionisation Constants of Organic Acids in Aqueous Solution, Pergamon Press, Oxford, 1979.
[13] D.H. Mc Daniel and H.C. Brown, J. Org. Chem. 23 (1958) 420.
[14] H.C. Brown and Y. Okamoto, J. Am. Chem. Soc. 80 (1958) 4979.
[15] (a) J.M. Dust and D.R. Arnold, J. Am. Chem. Soc. 105 (1983) 1221 and 6531; (b) D.D.M. Wayne and D.R. Arnold, Can. J. Chem. 62 (1984) 1164; (c) D.R. Arnold in H.G. Viehe, Z. Janousek and R. Merenyi (Ed.), Substituent Effects in Radical Chemistry, Riedel, Dordrecht, 1986, p. 171.
[16] G. Galliani and B. Rindone, J. Chem. Soc., Perkin. Trans. II, (1976) 1803.
[17] J.T. Groves and D.V. Subramanian, J. Am. Chem. Soc., 106 (1984) 2177.
[18] A.D. Adler, J. Org. Chem., 32 (1967) 476.
[19] K. Kalyanasundaram, Inorg. Chem., 23 (1984) 2453.
[20] P. Hambright, T. Gore and M. Burton, Inorg. Chem., 15 (1976) 2314.
[21] P. Hambright, A. Adeyemo, A. Shamim and S. Lemelle, Inorg. Synth., 23 (1985) 56.
[22] R.F. Pasternack, P.R. Huber, P. Boyd, G. Engasser, L. Francesconi, E. Gibbs, P. Fasella, G.C. Venturo and L. de C. Hinds, J. Am. Chem. Soc., 13 (1972) 4511✠✠.
[23] O. Herrmann, S. Husain Mehdi, A. Corsini, Can. J. Chem., 56 (1978) 1084.