Catalysis Letters 3 (1989) 389–398

HALOGEN SUBSTITUENT EFFECTS ON THE CATALYTIC ACTIVITY OF IRON PORPHYRIN COMPLEXES FOR SELECTIVE AIR-OXIDATION OF ALKANES IN THE LIQUID PHASE

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Received 30 May 1989; accepted 10 October 1989

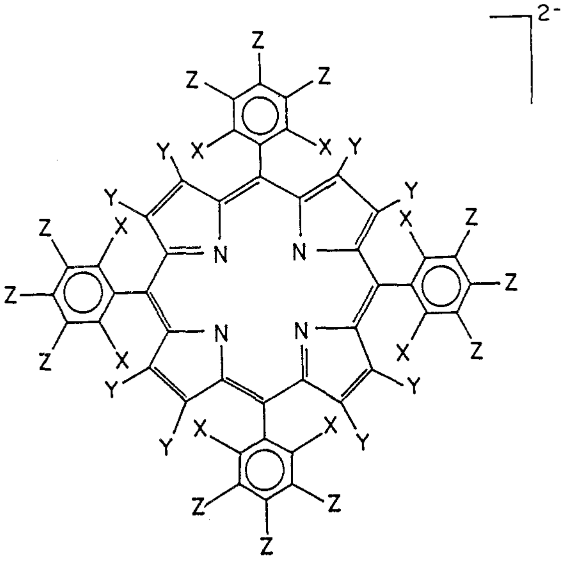
Halogenation of the porphyrin ring of porphyrinatoiron(III) complexes greatly increases their catalytic activity for the selective mild reaction of alkanes with molecular oxygen. The greater the halogen content the greater is the catalytic activity of the complex. Selective reaction of isobutane and propane with molecular oxygen is catalyzed by *tetrakis*(pentafluorophenyl)porphyrinatoiron(III) azido, hydroxo, or halo complexes under mild conditions of temperature and pressure. No added co-reductant is required in these systems. Catalytic oxidation of isobutane in the presence of *tetrakis*(pentafluorophenyl)porphyrinatoiron(III) hydroxide at room temperature gave *tert*-butyl alcohol in 95% selectivity. The catalyst activity was virtually unchanged after over 140 hours at room temperature and over 12,000 turnovers (moles of alcohol produced/mole of metal complex used) of isobutane to the alcohol were observed.

Iron porphyrin complexes, oxidation of alkanes

1. Introduction

Selective catalytic oxidation of light alkanes to alcohols using air or oxygen is an important chemical challenge. Much excellent work using biological [1,2], biomimetic [3,4] and abiotic [5–8] catalyst systems has provided the expectation that this challenge might soon be met in a synthetically useful manner. Recent communications from our laboratory have shown that tetraphenylporphyrinatoiron(III) azide is capable of efficiently catalyzing reaction of isobutane with molecular oxygen to give *tert*-butyl alcohol [9]. Furthermore, the *tetrakis* (pentafluorophenyl)porphyrinato iron (III) azide was found to be far more effective catalyst giving hundreds of turnovers at temperatures as low as room temperature [10]. The presence of perfluorophenyl substituents on the *meso*-position of the porphyrin so greatly enhanced catalytic activity, that even propane could be selectively air-oxidized under mild conditions [11].

Because of the pronounced enhancement of the catalytic activity of iron porphyrin complexes for reaction of alkanes with molecular oxygen by fluorinat-



LIGAND	X	Y	Z
(TPP)	8H	8H	12H
(TPPβ-Br$_4$)	8H	4H,4Br	12H
(TPPCl$_8$)	8Cl	8H	12H
(TPPCl$_8$β-Br$_4$)	8Cl	4H,4Br	12H
(TPPF$_{20}$)	8F	8H	12F

Fig. 1. Halogenated porphyrinato ligand systems for iron(III) complexes used to catalyze alkane oxidation.

ing the *meso*-phenyl substituent, it was of interest to determine the effect of other halogens both in the porphyrin ligand as well as in the axial position of the complex. In this communication we report that the greater the extent of halogenation of the tetraphenylporphyrinato, (TPP), ligand system, fig. 1, the greater is the catalytic activity of the complex for air-oxidation of alkanes. The specific nature of the halogen in the axial position, on the other hand does not greatly affect the catalytic activity of iron *tetrakis*(pentafluorophenyl)porphyrinato, Fe(TPPF$_{20}$) complexes.

2. Experimental

Iron(III)porphyrin azide and halide complexes were prepared by metathesis of the corresponding iron(III)porphyrin chloride or μ-oxo complex with the appropriate acid, HX (X = F, Cl, Br, N$_3$) (10% aqueous solution) in methylene chloride. Iron (III) porphyrin hydroxide complexes were prepared by treatment of the iron(III) porphyrin chloride with aqueous KOH in methylene chloride [12]. The μ-oxo complex: $[Fe(TPP\beta\text{-}Br_4)]_2O$ was prepared using the method of Callot [13]. Preparation of ($TPPCl_8$, β-Br_4) complexes was achieved by bromination of $Zn(TPPCl_8)$ with NBS [14] followed by iron insertion using the $FeCl_2$/DMF method [15].

Oxidations were carried out in a barricaded high pressure laboratory since some reactions were conducted within the explosion limits. Reactions reported in tables 1 and 3 were carried out in 50 cc Fisher-Porter glass aerosol tubes with magnetic stirring. Reactions reported in tables 2, 4, and 5 were conducted in a glass lined autoclave with teflon coated internals (impeller, dip-tube, etc.). Gas and liquid products were analyzed by a combination of standardized gc, ms, and gcms analysis.

3. Results

Table 1 shows that replacement of four of the β- (pyrrolic) hydrogen atoms with bromine substituents increases catalytic activity of porphyrinato complexes toward hydroxylation of isobutane. Replacement of the eight *ortho*-hydrogens of the *meso*-phenyl groups with chloro substituents gives complexes with even

Table 1
Effect of ring halogenation on the isobutane oxidation activity of porphyrinato iron (III) complexes [a]

Catalyst	mmoles	O_2 uptake, mmoles	TON [b]	Selectivity [c] to TBA, %
Fe(TPP)Cl	0.025	0.0	0	–
$Fe(TPP\beta\text{-}Br_4)Cl$	0.013	2.0	155	–
$Fe(TPPCl_8)Cl$	0.019	5.0	260	89
$Fe(TPPCl_8, \beta\text{-}Br_4)Cl$	0.020	17.3	865	83
$Fe(TPPF_{20})Cl$	0.016	32.6	2040	90
$Fe(TPP)N_3$	0.013	1.7	130	92
$Fe(TPP\beta\text{-}Br_4)N_3$	0.013	2.3	180	–
$Fe(TPPCl_8)N_3$	0.023	15.0	650	80
$Fe(TPPCl_8, \beta\text{-}Br_4)N_3$	0.023	21.5	930	82
$Fe(TPPF_{20})N_3$	0.016	33.0	2060	89
$[Fe(TPP)]_2O$	0.019	0	0	–
$[Fe(TPP\beta\text{-}Br_4)]_2O$	0.013	0	0	–
$Fe(TPPCl_8)OH$	0.013	9.2	710	83
$[Fe(TPPF_{20})]_2O$	0.013	24.0	1850	84
$Fe(TPPF_{20})OH$	0.013	29.2	2245	82

[a] A solution of the catalyst in 25 ml benzene containing 6 grams of isobutane was stirred at 80 °C under 100 psig of O_2 for 6 hours.

[b] moles O_2 consumed/mole catalyst used.

[c] (moles *t*-butyl alcohol produced/total moles liquid product) × 100.

Table 2
Effect of ring halogenation on the propane oxidation activity of porphyrinato iron (III) complexes [a]

Catalyst	mmoles	T, hrs.	TON [b]	IPA/acetone
Fe(TPP)Cl	0.023	3	2	na
Fe(TPPβ-Br_4)Cl	0.023	3	0	–
Fe($TPPCl_8$)Cl	0.023	6	0	–
Fe($TPPCl_8$, β-Br_4)Cl	0.023	3	125	1.0
Fe($TPPF_{20}$)Cl	0.023	3	230	0.8
Fe(TPP)N_3	0.023	3	0	–
Fe(TPPβ-Br_4)N_3	0.023	3	0	–
Fe($TPPCl_8$)N_3	0.023	4.5	0	–
Fe($TPPCl_8$, β-Br_4)N_3	0.023	4.5	250	0.8
Fe($TPPF_{20}$)N_3	0.023	3	330	0.8
[Fe(TPP)]$_2$O	0.023	3	0	–
[Fe(TPPβ-Br_4)]$_2$O	0.023	4.5	0	–
Fe($TPPCl_8$)OH	0.023	4.5	0	–
[Fe($TPPF_{20}$)]$_2$O	0.013	3	440	0.8
Fe($TPPF_{20}$)OH	0.013	3	270	0.6

[a] Stirred a solution of the catalyst in 60 grams of propane in 48 ml benzene at 125°C under 1000 psig air.

[b] moles (isopropyl alcohol + acetone) formed/mole catalyst used.

greater activity. If four of the β-hydrogens in the octachloro TPP are replaced with bromine atoms, activity is enhanced still further. Finally, as we have previously reported, the complex in which all twenty hydrogens in the *meso*-phenyl groups have been replaced by fluorine atoms has the highest activity of this series. Table 2 shows the very same trend for propane oxidation, however, since the less reactive secondary C–H bonds put a more severe demand on catalytic activity,

Table 3
Effect of the axial halide on isobutane oxidation activity of porphyrinato iron (III) complexes [a]

Catalyst	mmoles	Reaction T, °C	O_2 uptake, mmoles	TON [b]	Selectivity to TBA, % [c]
Fe($TPPF_{20}$)F	0.013	77	22.3	1710	83
Fe($TPPF_{20}$)Cl	0.013	77	24.2	1860	83
Fe($TPPF_{20}$)Br	0.013	77	24.9	1910	85
Fe($TPPF_{20}$)F	0.013	57	10.1	780	89
Fe($TPPF_{20}$)Cl	0.013	57	10.4	800	90
Fe($TPPF_{20}$)Br	0.013	57	6.6	510	87

[a] A solution of the catalyst in 25 ml benzene containing 6 grams of isobutane was stirred at temperature under 100 psig of O_2 for 6 hours. Products were analyzed by standardized glpc.

[b] moles O_2 consumed/mole catalyst used.

[c] (moles *t*-butyl alcohol producted/total moles liquid product) × 100.

Table 4

Effect of the axial halide on the propane oxidation activity of porphyrinato iron (III) complexes [a]

Catalyst	mmoles	*T*, hrs.	TON [b]	IPA/acetone
Fe(TPPF$_{20}$)F	0.023	4.5	630	0.9
Fe(TPPF$_{20}$)Cl	0.023	3.0	230	0.8
		4.5	390	0.8
Fe(TPPF$_{20}$)Br	0.023	4.5	390	0.8

[a] Stirred a solution of the catalyst in 60 grams of propane in 48 ml benzene at 125 °C under 1000 psig air.

[b] moles (isopropyl alcohol + acetone) formed/mole catalyst used.

many complexes with low activity for isobutane oxidation are not catalysts for propane oxidation under mild conditions.

Tables 3 and 4 indicate that the axial halide is not an important determinant of catalytic hydroxylation activity. When the complexes: Fe(TPPF$_{20}$)X (X = F, Cl, Br) were used as catalysts for isobutane oxidation at 80 °C, 1700–1900 moles of oxygen were consumed per mole catalyst used in six hours. Catalyst turnovers using the same three halides for propane oxidation at 125 °C varied

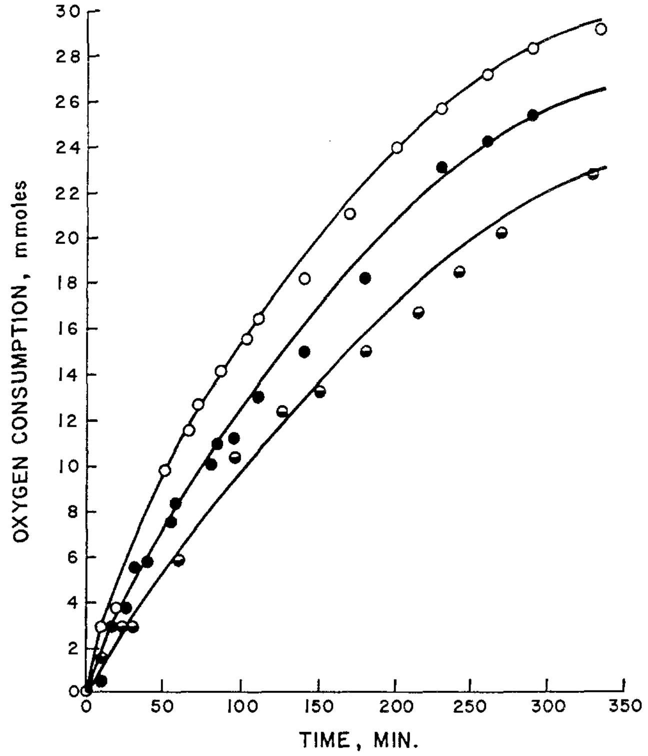


Fig. 2. Oxidation of isobutane catalyzed by Fe(TPPF$_{20}$)X. $T = 76$ °C, $P = 6.5$ atm., ○, X = ●H; ○, X = N$_3$; ⊖, X = Br.

Table 5
Fe(TPPF$_{20}$)OH-catalyzed isobutane oxidations [a]

Cat mmoles	Charge to rctr,		mmoles BzH (ml)	Reaction products, mmoles				Conversion i-C_4H_{10}, %	Selectivity TBA, %	TON [b]
	iC_4H_{12}	O_2		TBA	Acetone	CO	CO_2			
0.06	1042	35	80	164	27.8	6.1	13.6	18	85	3,195
	1046	52	80	173	29.8	5.9	16.7	19	85	3,385
	1051	56	80	180	41.9	7.7	16.9	21	81	3,695
	1034	102	80	146	35.9	7.5	18.8	17	80	3,040
	1041	212	80	123	26.7	5.7	18.0	14	82	2,495
	1037	212	80	114	23.3	4.4	13.9	13	83	2,290
	1243	56	60	190	28.4	5.3	18.5	17	86	3,640
	1458	53	40	238	32.0	5.4	16.8	18	88	4,510
	1660	53	20	262	30.0	6.5	18.3	17	89	4,880
	1872	53	0	376	58.1	8.7	32.6	23	86	7,230
0.03	1869	53	0	310	45.7	6.7	17.7	17	87	11,330
0.03 +	1871	53	0	332	16.7	0	17.7	18	95	12,150

[a] Isobutane was oxidized by an oxygen-containing gas mixture (75 atm, diluent = N_2) in the liquid phase (180 ml) for 3 hours at 80 ° C. Oxygen added as consumed.

[b] moles (TBA + acetone)/mole catalyst used.

+ Reaction temperature = 24 ° C; reaction time = 143 hrs.

from about 400–600 moles oxidate produced per mole catalyst in 4.5 hours. In fact, there was little difference between the activities of the Fe(TPPF$_{20}$) halides and the azido, μ-oxo or hydroxo complexes suggesting that TPPF$_{20}$ complexes of any of these axial anions might all go through a common intermediate in the catalytic cycle. A characteristic which appears to differentiate porphyrinatoiron (III)-catalyzed reactions of alkanes with molecular oxygen from classical radical-initiated autoxidation is that most of these reactions exhibit no apparent induction periods, fig. 2.

Table 5 shows that reactions of isobutane with molecular oxygen catalyzed by Fe(TPPF$_{20}$)OH proceed far faster in the absence of benzene as a solvent. Reactions carried out in neat isobutane produce more than 11,000 turnovers to *tert*-butyl alcohol in three hours at 80 ° C. Perhaps even more suprising is the fact that isobutane can be hydroxylated with dilute air at room temperature to give over 12,000 turnovers producing *tert*-butyl alcohol in 95% selectivity. After over five days on stream, no apparent catalyst deactivation was noticed. Analysis of the reaction mixture by UV/visible spectroscopy showed that at least 90% of the porphyrinatoiron system remained. *The efficient catalytic hydroxylation of an unactivated alkane with molecular oxygen at room temperature is unprecedented to our knowledge.*

4. Discussion

It has been shown [14,16,17] that electron withdrawing groups (fluoride, chloride, and bromide) on the porphyrinato ligand of iron(III) complexes enhance the rate of alkane hydroxylation using iodosylbenzene as the primary oxidant. Iron oxo complexes have been implicated as reaction intermediates in oxidations using single oxygen atom donors as oxidants [18]. Two reasons were advanced for the increase in catalyst activity with porphyrin halogenation. First it was suggested [17] that electron-withdrawing halogen substituents may activate the ferryl intermediate and increase its reactivity toward hydrocarbon. Secondly, by removing electron density from the ring, the halogens were thought to make the porphyrin less susceptible to electrophilic attack by the ferryl species leading to destruction of the catalyst.

It is of interest that we observe the same effect of increased activity as a function of halogen substitution on the porphyrin when porphyrinato iron complexes catalyze alkane oxidation using molecular oxygen as the oxidant. It is, therefore, tempting to speculate on the possible intermediacy of a high oxidation state iron oxo in the reactions of alkanes with molecular oxygen. Figure 3 shows a possible way in which a high oxidation state iron oxo complex might be generated by reaction with molecular oxygen and how it could participate in the catalytic oxidation of an alkane.

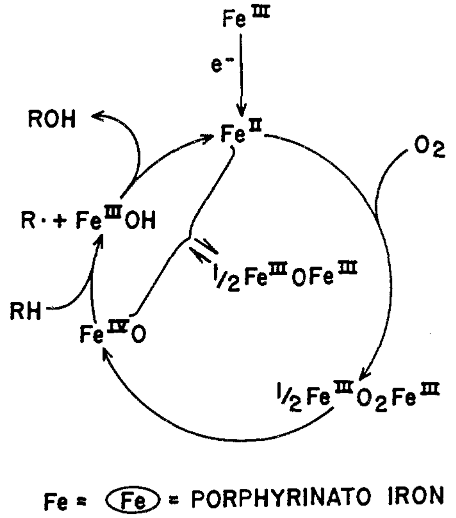


Fig. 3. Possible catalytic reaction pathway for alkane oxidations catalyzed by halogenated porphyrinato iron(III) complexes.

There are two additional reasons why halogenation of the TPP ligand might increase the observed number of catalytic turnovers in the air-oxidation of alkanes. Halogenation could shift the position of equilibrium away from the μ-oxo di-iron(III) species in favor of a low oxidation state iron(II) complex and a high oxidation state iron(!V) ferryl complex. Both steric and electronic factors could destabilize the diiron μ-oxo complex toward disproportionation. Electron withdrawal from the porphyrinato ligand should make it more difficult for oxidation of the ligand by electron transfer to the iron center. Thus, perhaps an iron(!V) ferryl species generated from symmetrical cleavage of a μ-peroxodimer [19] of a halogenated TPP could survive and be effective in alkane hydroxylation. The reductant, which initially converts Fe(III) to Fe(II) need only be present in small amounts, and might either be an adventitious impurity or, perhaps, the alkane itself. Electrochemical studies which will be reported elsewhere [20] have shown that halogenation of the porphyrin greatly increases the reduction potential of the $Fe^{+3/+2}$ couple [Fe(III) + $e^- \rightarrow$ Fe(II), fig. 3].

5. Conclusions

Biomimetic catalysis of alkane hydroxylations which have been carried out to data require either the stoichiometric consumption of a co-reductant system which supplies two electrons and two protons and produces equimolar amounts of water together with the organic oxidation product, or the stoichiometric consumption of a single oxygen-atom donor agent such as iodosylbenzene, hypochlorite, or a peroxidic substrate. These requirements impose practical limitations on a catalytic alkane oxidation especially for industrial practice. Alkane autoxidations promoted either by metal complexes or radical initiators often do not provide the selectivity desired for a synthetically superior process. Halogenation of porphyrinato iron(III) complexes produces highly active catalysts for the air-oxidation of light alkanes under mild conditions in a selective manner without the need for costly co-reductants or oxygen-atom transfer reagents. The greater the extent of porphyrin halogenation the greater is both the catalyst life and activity. Similarities between the behavior of these halogenated porphyrin complexes and known biomimetic catalyst systems suggest that they may have some mechanistic features in common.

Work continues to prepare even more active iron centers in stable macrocyclic ligand environments for use as catalysts for the low temperature selective air-oxidation of alkanes.

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