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Lewis acid assisted permanganate oxidations

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Abstract—Lewis acids combine with permanganate in acetone solutions to form a complex that has enhanced oxidizing capabilities. The use of Lewis acids under these conditions to promote permanganate oxidations is superior to the use of Bronsted acids because the latter promote enolization of the solvent and subsequent unproductive reduction of the oxidant. The products obtained from a variety of alkenes, alkynes, arenes, sulfides, alcohols and ethers have been identified and probable reaction mechanisms proposed. © 2002 Elsevier Science Ltd. All rights reserved.

1. Introduction

The literature on the use of Lewis acids to promote permanganate oxidations is limited to two studies—one on the oxidation of sulfides, the other on the oxidation of alkanes. In 1994, Block and co-workers reported that thioanisole was resistant to oxidation by permanganate under mild conditions unless a Lewis acid such as iron(III) chloride was present.[1] Subsequently, Xie and co-workers, using zinc chloride as a catalyst, showed that the reaction followed a two-step mechanism as outlined in Scheme 1.[2] From a detailed study of the reaction kinetics, it was established that the catalytic function of the Lewis acid is associated with an interaction between it and the oxidant. The effect of this interaction is to produce a reactive permanganate/zinc chloride complex, **1**. The Lewis acid, therefore, functions in much the same way as Bronsted acids, which react with MnO_4^- to form $HMnO_4$,[3] a process that is responsible for the acid catalysis observed during permanganate oxidations.[4]

$$MnO_4^- + ZnCl_2 \rightleftharpoons \underset{\mathbf{1}}{MnO_4ZnCl_2^-}$$

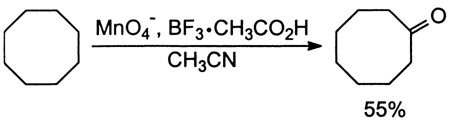
$$MnO_4ZnCl_2^- + R_2S \xrightarrow{slow} R_2SO + MnO_3ZnCl_2^-$$

$$R_2SO + MnO_4ZnCl_2^- \longrightarrow R_2SO_2 + MnO_3ZnCl_2^-$$

$$MnO_3ZnCl_2^- \xrightarrow{solvent} MnO_2ZnCl_2$$

Scheme 1. Proposed mechanism for Lewis acid catalysis during the oxidation of sulfides by permanganate.[2]

Lau, Wu, Bai and Mak have also reported that boron trifluoride assists the oxidation of alkanes by permanganate. Oxidation of cyclooctane gives cyclooctanone (Eq. (1)) while both 2-hexanone and 3-hexanone are obtained from hexane (Eq. (2)).[5]



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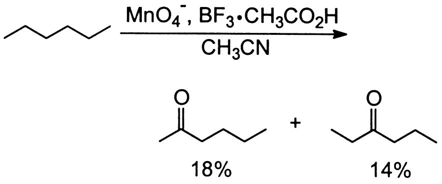

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In this paper, the scope, limitations and utility of Lewis acid assisted permanganate oxidations are explored.

2. Results and discussion

2.1. Oxidation of sulfides

The previously reported catalytic effect of iron(III) chloride on the permanganate oxidation of sulfides was confirmed using benzyl phenyl sulfide as a typical reductant. From the results summarized in Table 1, it can be seen that treatment of benzyl phenyl sulfide with permanganate and iron(III) chloride in either acetone or acetonitrile gives a quantitative yield of the corresponding sulfone. However, under the same conditions, but in the absence of iron(III) chloride, the yields are reduced.

The mechanism of this reaction was investigated by studying the products obtained from the oxidation of a

Keywords: permanganate; Lewis acid; oxidation; catalysis; iron(III) chloride.

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Table 1. The effect of iron(III) chloride on the oxidation of benzyl phenyl sulfide by potassium permanganate

Oxidant	Catalyst	Solvent	Yield (%)[a]
$KMnO_4$ (50 mg)	$FeCl_3$ (5 mg)[b]	Acetone	98
$KMnO_4$ (50 mg)	None[b]	Acetone	8
$KMnO_4$ (50 mg)	$FeCl_3$ (5 mg)[c]	Acetonitrile	100
$KMnO_4$ (50 mg)	None[c]	Acetonitrile	58

Benzyl phenyl sulfide (0.10 mmol) was treated with oxidant and catalyst for 75 min.

[a] The product is benzyl phenyl sulfone.

[b] Temperature: 0°C.

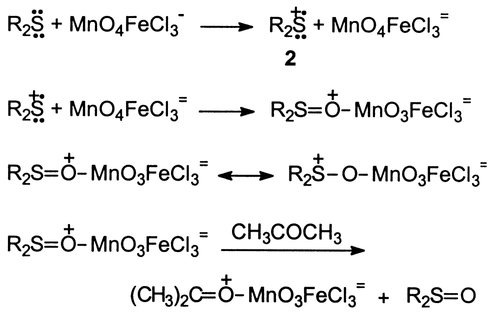
[c] Temperature: 23°C.

number of sulfides with particular structures. If the reaction is initiated by a single electron transfer (SET), an intermediate radical cation, **2**, would be formed by loss of an electron from the sulfur. This intermediate could then participate in an oxygen rebound[6] step to give oxidized products as in Scheme 2.

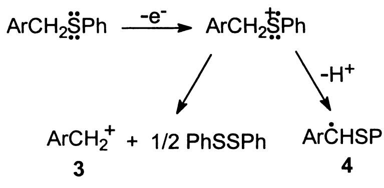
In an attempt to find evidence for or against a SET mechanism, a study was made of the oxidation of sulfides which on loss of an electron give radical cations that can easily undergo side reactions. For example, the radical cations formed from methoxy-substituted benzyl phenyl sulfides can react by heterolytic C–S bond cleavage to give carbocations, **3**, or by proton loss to give free radicals, **4**, as depicted in Scheme 3.[7,8]

Heterolytic C–S bond cleavage is promoted by the presence of a *p*-methoxy substituent which can contribute to the stability of the carbocation, **3**. In the presence of water, **3** would react to give a substituted benzyl alcohol, while in the presence of nitrate or acetate ions, the corresponding esters would be formed as in Scheme 4.

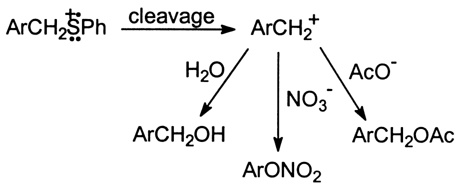
Thus, the formation of products other than sulfoxides and sulfones would be expected if *p*-methoxybenzyl phenyl sulfide was oxidized in a reaction initiated by electron transfer. Confirmation of this possibility was obtained when the products from the oxidation of *p*-methoxybenzyl phenyl sulfide by typical one-electron transfer oxidants such as cerium(IV) and manganese(III) were identified. For example, products obtained when cerium(IV) ammonium nitrate is the oxidant included *p*-methoxybenzyl nitrate and *p*-methoxybenzyl acetate (when acetic acid was present in the solvent). Similarly, as indicated from the data in Table 2, *p*-methoxybenzyl alcohol is produced when *p*-methoxybenzyl phenyl sulfide is oxidized by manganese(III) fluoride in a wet solvent.



Scheme 2. SET mechanism.

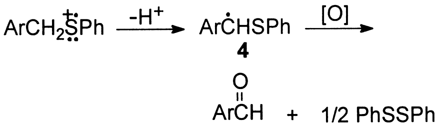


Scheme 3. Expected intermediates from a SET oxidation of methoxy-substituted benzyl phenyl sulfides ($ArCH_2SPh$).



Scheme 4. Products expected if heterolytic C–S cleavage occurs.

Methoxy groups in the *meta* positions should increase the acidity of the benzyl hydrogens in the radical cation, thus promoting formation of the corresponding free radical, **4**. From other studies, it is known that **4** is very easily oxidized to an aldehyde and diphenyl disulfide as in Eq. (3).[7] Therefore, the formation of a radical cation intermediate, followed by proton loss can also result in the formation of cleavage products (aldehydes and diphenyl disulfide).



(3)

This possibility was confirmed when it was observed that 3,4,5-trimethoxybenzaldehyde is the major product formed when 3,4,5-trimethoxybenzyl phenyl sulfide is oxidized by either cerium(IV) or manganese(III) (Table 3).

In contrast to the products obtained when methoxy-substituted benzyl phenyl sulfides are oxidized by cerium(IV) and manganese(III), virtually no cleavage products are obtained when $MnO_4FeCl_3^-$ is used as the oxidant (Tables 2 and 3). In this respect, permanganate resembles other oxidants such as ruthenium tetroxide and tetrapropylammonium perruthenate that are believed to react with sulfides via a concerted oxygen transfer mechanism.[9]

This conclusion is also consistent with previously reported Hammett studies. If the reaction proceeded by a SET mechanism with formation of radical cations in the rate limiting step, the transition state could be stabilized by direct resonance interactions as illustrated in Eq. (4). The rates of reaction would, therefore, be expected to correlate best with Hammett σ^+ substituent constants. Such correlations have been previously observed for other oxidation reactions that are known to proceed by SET mechanisms.[10,11] However, the rates of oxidation of a series of substituted thioanisoles by permanganate in an acetone solution containing zinc chloride as the catalyst exhibits a better correlation with σ substituent constants.[2] Similarly, the rates of oxidation of a series of substituted phenyl thioacetic

Table 2. Product ratios for the oxidation of 4-methoxybenzyl phenyl sulfide

Oxidant	Solvent	Sulfoxide[a]	Sulfone[b]	Aldehyde[c]	Alcohol[d]	Nitrate[e]	Acetate[f]
$(NH_4)_2Ce(NO_3)_6$	CH_3CN	0.24		0.40		0.72	
$(NH_4)_2Ce(NO_3)_6$	$CH_3CN/AcOH$		0.05	0.22			0.73
MnF_3	CH_3CN/H_2O			0.59	0.41		
MnF_3	$CH_3CN/AcOH$			0.85			0.15
$KMnO_4/FeCl_3$	CH_3COCH_3		1.00				

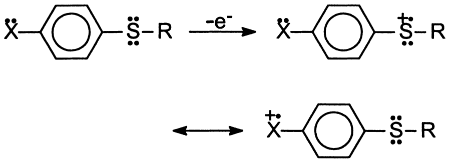
[a] 4-Methoxybenzyl phenyl sulfoxide.
[b] 4-Methoxybenzyl phenyl sulfone.
[c] 4-Methoxybenzaldehyde.
[d] 4-Methoxybenzyl alcohol.
[e] 4-Methoxybenzyl nitrate.
[f] 4-Methoxybenzyl acetate.

Table 3. Product ratios for the oxidation of 3,4,5-trimethoxybenzyl phenyl sulfide

Oxidant	Solvent	Sulfone[a]	Aldehyde[b]	Nitrate[c]
$(NH_4)_2Ce(NO_3)_6$	CH_3CN		1.00	
$(NH_4)_2Ce(NO_3)_6$	$CH_3CN/AcOH$		0.80	0.20
MnF_3	CH_3CN		0.21	
$KMnO_4/FeCl_3$	CH_3COCH_3	0.97	0.03	

[a] 3,4,5-Trimethoxybenzyl sulfone.
[b] 3,4,5-Trimethoxybenzaldehyde.
[c] 3,4,5-Trimethoxybenzyl nitrate.

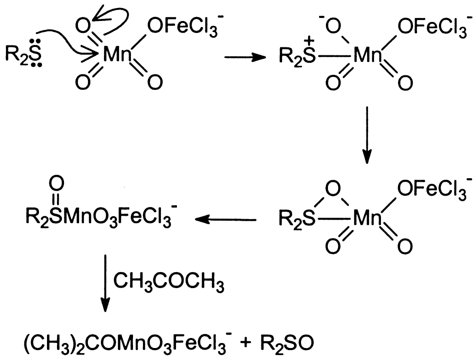
acids ($PhSCH_2CO_2H$) by permanganate in aqueous solutions also correlates better with Hammett σ substituent constants.[12]



(4)

While these results do not completely rule out an initial SET followed by an unusually rapid oxygen rebound, it appears most probable that permanganate oxidations of sulfides proceed by way of a concerted oxygen transfer mechanism.[9] Such a reaction would most likely occur by ligation with expansion of the coordination number of manganese from 4 to 5 as in Scheme 5.[2]

Since the ultimate product obtained is a sulfone, the initially formed sulfoxide must undergo a subsequent rapid oxidation (Eq. (5)). This conclusion is consistent with competitive experiments in which compounds containing both sulfide and sulfoxide functionalities are oxidized (Eqs. (7)–(9)).[1,13,14] In each example, the sulfoxide is preferentially oxidized.

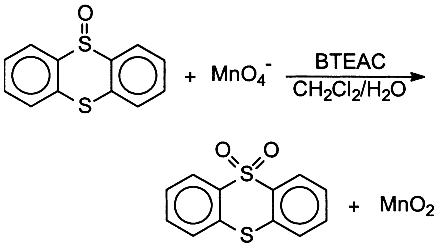


Scheme 5. Probable mechanism for the iron(III) chloride catalyzed oxidation of sulfides by permanganate.

$$R_2SO + MnO_4{\cdot}FeCl_3^- \longrightarrow R_2SO_2 + MnO_2{\cdot}FeCl_3 \qquad (5)$$

$$CH_3SCH_2SOCH_3 + MnO_4^- \xrightarrow{CH_3COCH_3/H_2O} CH_3SCH_2SO_2CH_3 + MnO_2 \qquad (6)$$

$$CH_3SOCH_2SCH_2SSCH_2SOCH_3 + MnO_4^- \xrightarrow{FeCl_3 \mid CH_3COCH_3} CH_3SO_2CH_2SCH_2SSCH_2SO_2CH_3 + MnO_2 \qquad (7)$$



(8)

BTEAC is benzyltriethylammonium chloride

Although transfer of an oxygen atom to sulfur should reduce permanganate to a manganese(V) compound, the observed product is invariably manganese(IV); i.e. MnO_2. This occurs because manganese(V) compounds are highly reactive oxidants which are rapidly reduced by reaction with the solvent.[15]

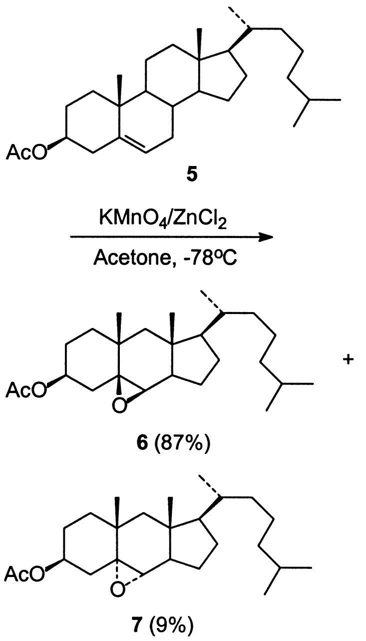
2.2. Oxidation of alkenes

The oxidation of cholesteryl acetate, **5**, by permanganate under mild conditions (acetone, <0°C) requires a Lewis acid; either iron(III) chloride or zinc chloride as in Eq. (9). The primary product is the β-epoxide, **6**; however, some of the corresponding α-epoxide, **7**, is also obtained with zinc chloride (Table 4).

Table 4. Products obtained from the oxidation of cholesteryl acetate by permanganate

Oxidant	β-Epoxide (**6**) (%)	α-Epoxide (**7**) (%)
$KMnO_4$ (50 mg), $FeCl_3$ (30 mg)	80	
$KMnO_4$ (50 mg), no Lewis acid	No reaction	
$KMnO_4$ (100 mg), $FeCl_3$ (100 mg)	95	
$KMnO_4$ (125 mg), $ZnCl_2$ (50 mg)	87	9

These reactions were stirred at −78°C for 2 h and then allowed to warm to room temperature with stirring over a 12 h period.

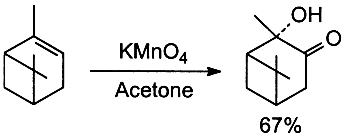


(9)

The oxidation of terminal aliphatic alkenes gives carboxylic acids as the primary products. For example, oxidation of 1-pentadecene and 1-dodecene by permanganate in acetone assisted by iron(III) chloride gives tetradecanoic and heneicosanoic acids, respectively, in good yields (Table 5). In this respect, the Lewis acid assisted reactions are similar to the reactions of permanganate in acidic aqueous solutions, where terminal alkenes are also cleaved to give carboxylic acids. The advantage of Lewis acids is associated primarily with the ability to use them in acetone where alkenes exhibit greater solubility. The use of Bronsted acids, in acetone, on the other hand, promotes enolization of the solvent and subsequent reduction of the oxidant in unproductive reactions.

The oxidation of nonterminal alkenes appears to proceed through a diketone intermediate to cleavage products (carboxylic acids). For example, the products obtained from 4-octene and 7-tetradecene are the corresponding carboxylic acids if sufficient oxidant is used over an extended time; however, if the amount of oxidant is limited or a reduced time period is used, the products are primarily the corresponding diketones, as illustrated by the data in Table 5.

Double bonds conjugated with aromatic rings (e.g. 1,1-diphenylethene and *p*-methoxycinnamic acid) are easily converted into the corresponding carbonyl compounds (benzophenone and *p*-methoxybenzaldehyde, respectively). However, use of Lewis acids does not improve the rates or yields of these reactions. Similarly, α-pinene is converted into the corresponding ketol in over 60% yield (Eq. (10)), but addition of a Lewis acid does not improve the reaction.



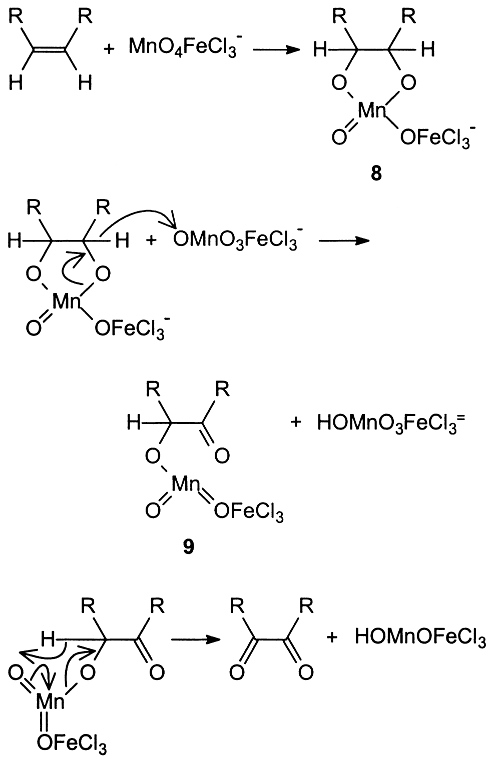
(10)

Although a great deal of experimental and theoretical information is available concerning the reaction of permanganate with alkenes, a completely satisfactory mechanism for the process that occurs under acidic conditions is not available. Under basic conditions, where the products are *cis*-diols, there is compelling evidence that the reaction proceeds via an intermediate cyclic manganese(V) diester as in Eq. (11).[16] It seems likely, therefore, that the reaction would be initiated under all conditions by formation of a similar intermediate. When

Table 5. Products obtained from the oxidation of linear alkenes

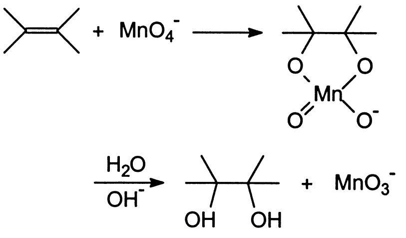
Alkene	Oxidant	Conditions[a] (h)	Products (yield)
1-Pentadecene	$KMnO_4$ (1.6 g), $FeCl_3$ (1.0 g)	1.5	Tetradecanoic acid (90%)
1-Pentadecene	$KMnO_4$ (1.6 g), no $FeCl_3$	1.5	No reaction
1-Pentadecene	$KMnO_4$ (1.6 g), $FeCl_3$ (1.0 g)	15	Teteradecanoic acid (85–90%)
1-Docosene	$KMnO_4$ (1.6 g), $FeCl_3$ (1.0 g)	1.5	Heneicosanoic acid (94%)
1-Docosene	$KMnO_4$ (1.6 g), no $FeCl_3$	15	No reaction
4-Octene	$KMnO_4$ (1.6 g), $FeCl_3$ (1.0 g)	15	Butanoic acid (85%)
4-Octene	$KMnO_4$ (1.6 g), $FeCl_3$ (1.0 g)	1.5	Butanoic acid (72%), 4,5-dioxooctane (24%)
4-Octene	$KMnO_4$ (1.6 g), $FeCl_3$ (1.0 g)	0.25	Butanoic acid (36%), 4,5-dioxooctane (60%)
4-Octene	$KMnO_4$ (0.8 g), $FeCl_3$ (0.4 g)	1.5	Butanoic acid (21%), 4,5-dioxooctane (75%)
4-Octene	$KMnO_4$ (0.4 g), $FeCl_3$ (0.2 g)	0.25	Butanoic acid (9%), 4,5-dioxooctane (61%)
4-Octene	$KMnO_4$ (0.2 g), $FeCl_3$ (0.1 g)	0.25	4,5-Dioxooctane (50%)
4-Octene	$KMnO_4$ (1.6 g), no $FeCl_3$	1.5	No reaction
7-Tetradecene	$KMnO_4$ (1.6 g), $FeCl_3$ (1.0 g)	15	Heptanoic acid (80–89%)
7-Tetradecene	$KMnO_4$ (1.6 g), $FeCl_3$ (1.0 g)	1.5	Heptanoic acid (70%), 7,8-dioxotetradecane (25%)
7-Tetradecene	$KMnO_4$ (1.6 g), $FeCl_3$ (1.0 g)	0.25	Heptanoic acid (37%), 7,8-dioxotetradecane (59%)
7-Tetradecene	$KMnO_4$ (0.8 g), $FeCl_3$ (0.4 g)	1.5	Heptanoic acid (39%), 7,8-dioxotetradecane (60%)
7-Tetradecene	$KMnO_4$ (1.6 g), no $FeCl_3$	1.5	No reaction

[a] These reactions were all carried out using 1 mmol of alkene in acetone (10 mL) by stirring for the indicated period of time at −78°C, followed by a gradual warm up to room temperature (~2 h) and additional stirring for 12 h.



Scheme 6. A plausible mechanism for the oxidation of alkenes to diones.

diones are the products, however, a 1:1 stoichiometry would result in the reduction of the oxidation state of manganese from 7 to 1. Moreover, when cleavage to carboxylic acids occurs manganese would be reduced to an oxidation state of −1 if a 1:1 stoichiometry was maintained (Eqs. (12) and (13)). Formation of compounds with manganese in 1 or −1 oxidation states is highly unlikely and it is, therefore, apparent that additional oxidant is required for these processes.



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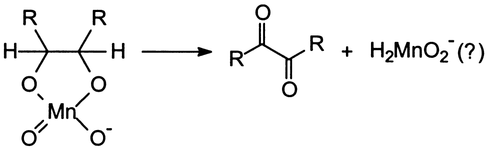

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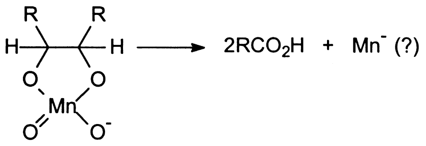


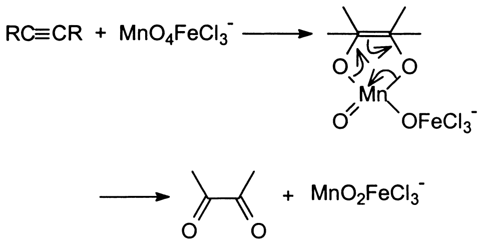
(13)

Since the product forming steps occur after the rate limiting step, they are not amenable to kinetic studies and, although theoreticians have successfully modeled the formation of the intermediate manganese(V) diester,[17] none, so far as we are aware, have reported studies on the subsequent, more interesting steps of the reaction.

A plausible mechanism for the oxidation of alkenes to diones, that does not require reduction of manganese to an unusually low oxidation state, is presented in Scheme 6. In this mechanism, it is assumed that the initially formed intermediate, **8**, reacts with additional oxidant by hydride transfer to give a second intermediate, **9**, which can hydrolyze to a ketol, as observed for compounds such as α-pinene that contain trisubstituted double bonds (Eq. (10)), or decompose to form a diketone and manganese(III).

2.3. The oxidation of alkynes

The oxidation of alkynes also gives diones in good yields (Table 6). Cleavage products (carboxylic acids) are obtained only if an excess of oxidant and a prolonged time is used. Since conversion of an alkyne into a dione is a four electron oxidation, it is possible that the reaction proceeds as in Eq. (14) without participation of additional oxidant. The manganese(III) product formed in this reaction would be readily oxidized to MnO_2 by permanganate.



(14)

2.4. The oxidation of arenes

Arenes are readily oxidized to the corresponding α-ketones as indicated by the data in Table 7. Although anhydrous iron(III) chloride has previously been used, the data in Table 7 indicate that the hexahydrate works equally well. This observation has the effect of relaxing the experimental conditions somewhat; it appears that the use of anhydrous conditions is not imperative for these reactions.

Table 6. Products obtained from the oxidation of alkynes

Alkyne	Oxidant	Conditions	Products (yield)
8-Hexadecyne	$KMnO_4$ (0.8 g), $FeCl_3$ (0.4 g)	1.3 h (−78°C), 1 h (0°C)	8,9-Dioxohexadecane (91%)
8-Hexadecyne	$KMnO_4$ (0.8 g), $FeCl_3$ (0.4 g)	15 h (−78°C)	Octanoic acid (89%), 8,9-dioxohexadecane (9%)
1-Phenyl-1-butyne	$KMnO_4$ (0.8 g), $FeCl_3$ (0.4 g)	15 h (−78°C)	1,2-Dioxo-1-phenylbutane (77%)
1-Phenyl-1-butyne	$KMnO_4$ (1.6 g), no $FeCl_3$	15 h (−78°C)	No reaction

Table 7. Products obtained from the oxidation of arenes

Arene	Oxidant[a]	Product (yield)
Diphenylmethane	$KMnO_4$ (1.6 g), $FeCl_3 \cdot 6H_2O$ (1.6 g)	Benzophenone (100%)
Diphenylmethane	$KMnO_4$ (1.6 g), no $FeCl_3$	Benzophenone (17%)
Pentylbenzene	$KMnO_4$ (2.0 g), $FeCl_3 \cdot 6H_2O$ (1.7 g)	1-Oxo-1-phenylpentane (85%)
Ethylbenzene	$KMnO_4$ (1.6 g), $FeCl_3 \cdot 6H_2O$ (1.6 g)	Acetophenone (100%)
Ethylbenzene	$KMnO_4$ (1.6 g), no $FeCl_3$	No reaction
4-Fluoroethylbenzene	$KMnO_4$ (1.6 g), $FeCl_3$ (1.0 g)	4-Fluoroacetophenone (94%)
4-Methylethylbenzene	$KMnO_4$ (1.6 g), $FeCl_3$ (1.0 g)	4-Methylacetophenone (100%)
2-Nitroethylbenzene	$KMnO_4$ (1.6 g), $FeCl_3$ (1.0 g)	2-Nitroacetophenone (23%)
Propylbenzene	$KMnO_4$ (1.6 g), $FeCl_3 \cdot 6H_2O$ (1.6 g)	1-Oxo-1-phenylpropane (82%)
1-Phenyldecane	$KMnO_4$ (1.6 g), $FeCl_3$ (1.0 g)	1-Oxo-1-phenyldecane (71%)
Isobutylbenzene	$KMnO_4$ (1.6 g), $FeCl_3$ (1.0 g)	1-Oxo-1-phenyl-2-methylpropane (57%)
Tetralin	$KMnO_4$ (1.6 g), $FeCl_3$ (0.4 g)	1-Tetralone (90%)
Indane	$KMnO_4$ (1.6 g), $FeCl_3$ (0.4 g)	1-Indanone (95%)
Isopropylbenzene	$KMnO_4$ (1.6 g), $FeCl_3$ (1.0 g)	Acetophenone (39%)
Isopropylbenzene	$KMnO_4$ (1.6 g), $FeCl_3 \cdot 6H_2O$ (1.6 g)	Acetophenone (40%)
sec-Butylbenzene	$KMnO_4$ (1.6 g), $FeCl_3$ (1.0 g)	1-Oxo-1-phenylpropane (18%)
Cyclohexylbenzene	$KMnO_4$ (1.6 g), $FeCl_3$ (1.6 g)	No reaction

[a] 1.0 mmol of arene and the oxidant were dissolved in acetone at −78°C and stirred for 2 h. The solution was allowed to warm to room temperature (~2 h) and stirred for an additional 12 h.

Previously reported studies indicate that the oxidation of arenes by permanganate is initiated by transfer of a hydrogen atom to the oxidant.[18] Subsequent oxidation of the intermediate free radical would give a carbocation which could then be converted into the corresponding ketone via an intermediate manganate(VII) ester, **10**, as illustrated in Scheme 7. As previously mentioned, the manganese(V) products ($HMnO_4FeCl_3^{=}$ and $HMnO_3FeCl_3$) produced in these reactions would be very reactive species; so reactive that they would readily be reduced by the solvent to give the observed product, MnO_2.[15]

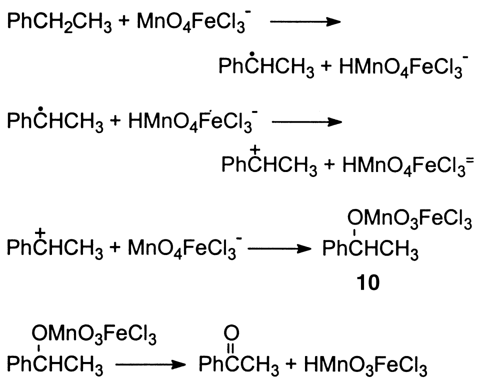
When the α-carbon is tertiary, as in isopropylbenzene or *sec*-butylbenzene, formation of the observed products, acetophenone and 1-oxo-1-phenylpropane, requires cleavage of a carbon–carbon bond in addition to C–H cleavage. Although the mechanism for this process has not been systematically investigated, a possibility consistent with the available evidence involves sequential hydrogen atom abstractions followed by rapid oxidative cleavage of the resulting alkene as in Scheme 8. The oxidation of 1,1-diphenylethene to benzophenone, which occurs very readily, serves as a model for the last step of the reaction in Scheme 8.

2.5. Oxidation of alcohols and ethers

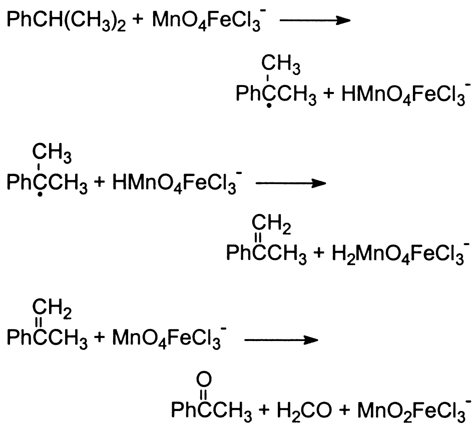
Alcohols and ethers are oxidized to the corresponding carbonyl compounds. As illustrated by the data in Table 8, alcohols yield aldehydes or ketones and ethers give esters or lactones. If these reactions are also initiated by a rate limiting hydrogen atom transfer followed by a SET, as suggested by evidence in the literature,[18] the mechanisms summarized in Schemes 9 and 10 may pertain.

2.6. Attempted oxidation of amines

The oxidation of primary aliphatic and aromatic amines such as cyclohexyl amine and aniline was also investigated. However, significant amounts of an identifiable product could be obtained for only one reaction (Eq. (15)). This failure to obtain useful amounts of products could be associated with the tendency of Lewis acids to form strong complexes with amines. If the Lewis acid is strongly complexed with an amine, it will not be able to activate the oxidant as in Scheme 1. This suggestion is consistent with the observation that the only amine to give an expected product was one in which the nitrogen lone pair is highly delocalized and therefore less available for complex formation. In any event, it is much better to use



Scheme 7. A possible mechanism for the oxidation of ethylbenzene.



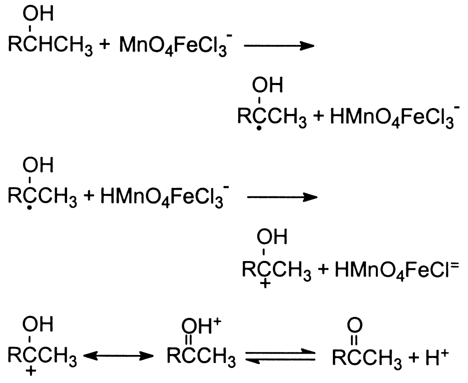
Scheme 8. A possible mechanism for the oxidation of isopropylbenzene.

Table 8. Products obtained from the oxidation of alcohols and ethers

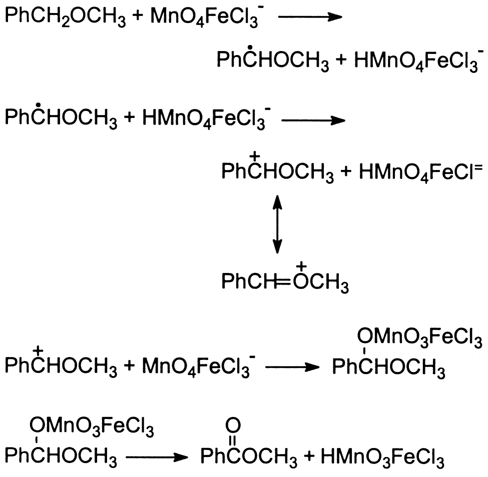
Reductant	Oxidant	Conditions[a] (h)	Products (yield)
2-Decanol	$KMnO_4$ (0.8 g), $FeCl_3$ (0.4 g)	2	2-Decanone (98%)
4-Methylbenzhydrol	$KMnO_4$ (0.8 g), $FeCl_3$ (0.4 g)	0.25	4-Methylbenzophenone (92%)
4-Methoxybenzyl alcohol	$KMnO_4$ (0.8 g), $FeCl_3$ (0.4 g)	0.67	4-Methoxybenzaldehyde (90%)
Tetrahydrofuran	$KMnO_4$ (1.6 g), $FeCl_3$ (1.0 g)	15[b]	2-Oxacyclopentanone (80%)
Tetrahydropyran	$KMnO_4$ (1.6 g), $FeCl_3$ (1.0 g)	15[b]	2-Oxacyclohexanone (83%)
3-Methyltetrahydropyran	$KMnO_4$ (1.6 g), $FeCl_3$ (1.0 g)	15[b]	2-Oxa-4-methylcyclohexanone (45%)
Benzyl phenyl ether	$KMnO^4$ (1.6 g), $FeCl_3$ (1.0 g)	15[b]	Phenyl benzoate (86%), benzaldehyde (10%)
Xanthene	$KMnO_4$ (1.6 g), $FeCl_3$ (1.0 g)	15[a]	Xanthone (96%)
Phthalan	$KmnO_4$ (1.6 g), $FeCl_3$ (1.0 g)	1	Phthalide (90%)
2,3-Dihydrobenzofuran	$KmnO_4$ (1.6 g), $FeCl_3$ (1.0 g)	1	No reaction

[a] The reactions were carried out using 1.0 mmol of reductant in acetone at −78°C.

[b] The reductant and oxidant were dissolved in acetone at −78°C and after stirring for about 10 min, the solution was allowed to warm slowly at room temperature over a period of 2 h.

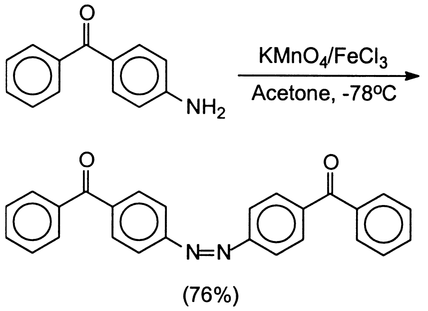


Scheme 9. A possible mechanism for the oxidation of alcohols.



Scheme 10. A possible mechanism for the oxidation of ethers.

heterogeneous conditions for the oxidation of amines by permanganate as previously reported.[19]



(15)

2.7. Summary

Lewis acids assist the oxidation of organic compounds by permanganate in acetone solutions. Under these conditions, sulfones are obtained from sulfides, diones and carboxylic acids from alkenes, diones from alkynes, α-ketones from arenes, aldehydes and ketones from alcohols, and esters and lactones from ethers. The oxidation of amines does not result in the formation of significant amounts of useful products.

The fact that the mechanisms of all of these reactions are not completely understood does not prevent their use in synthetic organic chemistry.

3. Experimental

3.1. Reductants

The reductants (sulfides, alkenes, alkynes, arenes, alcohols, ethers and amines) were obtained commercially and subjected to additional purification as required. Solvents, Lewis acids and permanganate were reagent grade. The methoxy substituted benzyl phenyl sulfides were prepared as described below.

4-Methoxybenzyl phenyl sulfide was prepared from the reaction of 4-methoxybenzyl chloride with thiophenol as follows.[20]

4-Methoxybenzyl chloride (0.64 g, 4.10 mmol) was added to a mixture of thiophenol (1.32 g, 12.00 mmol) and potassium carbonate (2.00 g, 14.47 mmol) in acetone (20 mL). The mixture was stirred under reflux for 5 h, filtered and the residue washed with methylene chloride (20 mL). The filtrate and washings were combined and concentrated. The resulting solid was purified by column chromatography (SiO_2; eluant 4:1 hexane/methylene chloride) to give a colorless solid (0.79 g, 3.4 mmol, 83%). The spectroscopic properties (^1H NMR and ^{13}C NMR) of this compound are consistent with its assigned structure and in agreement with those described in the literature.[20]

3,4,5-Trimethoxybenzyl phenyl sulfide was prepared from the reaction of 3,4,5-trimethoxybenzyl alcohol with thiophenol as described in the literature.[21]

p-Toluenesulfonic acid (0.10 g) was added to a stirred solution of 3,4,5-trimethoxybenzyl alcohol (1.02 g, 5.15 mmol) and thiophenol (1.07 g, 9.73 mmol) in benzene (20 mL). The resulting mixture was stirred under reflux for 1 h and concentrated to give a yellow oil. Purification by column chromatography (SiO_2; eluant 4:1 hexane/methylene chloride) gave a colorless solid (1.24 g, 4.28 mmol, 83%). The spectroscopic properties (^1H NMR and ^{13}C NMR) of this compound are consistent with its assigned structure and in agreement with those described in the literature.[21]

3.2. Calculation of product ratios

Since extensive work-up procedures could alter the composition of the product mixtures, various methods for analyzing the crude products were investigated. Of the approaches considered, it was found that use of ^1H NMR integrals provided the most reliable measurements of the relative amounts of product present. When artificially prepared product mixtures were used, the ^1H NMR integrals reproduced the known product ratios within ±3%. For all products, except aldehydes, the signals from the benzylic hydrogens were in regions where the integrals could be accurately measured; for aldehydes, the integral for the hydrogen attached to the carbonyl was used. The product ratios were then calculated by taking the integral for a particular product over the sum of the integrals for all of the other products, the aldehyde integrals being doubled. The ^1H NMR signals used are found at the following chemical shifts: benzyl phenyl sulfide (δ=4.22), benzyl phenyl sulfoxide (δ=3.94–4.18), benzyl phenyl sulfone (δ=4.31), benzaldehyde (δ=10.03), 4-methoxybenzyl phenyl sulfide (δ=4.10), 4-methoxybenzyl phenyl sulfoxide (δ=3.87–4.08), 4-methoxybenzyl phenyl sulfone (δ=4.24), 4-methoxybenzyl nitrate (δ=5.35), 4-methoxybenzyl acetate (δ=5.04), 4-methoxybenzyl alcohol (δ=4.48), 4-methoxybenzaldehyde (δ=9.90), 3,4,5-trimethoxybenzyl phenyl sulfide (δ=4.02), 3,4,5-trimethoxybenzyl phenyl sulfoxide (δ=3.86–4.08), 3,4,5-trimethoxybenzyl phenyl sulfone (δ=4.23), 3,4,5-trimethoxybenzyl nitrate (δ=5.29) and 3,4,5-trimethoxybenzaldehyde (δ=9.86). All spectra were recorded on a Bruker AC-200 spectrometer using $CDCl_3$ as the solvent.

Diphenyl disulfide was also produced as a coproduct in many of the reactions. Although its presence could easily be detected using TLC, its ^1H NMR signals were not sufficiently distinct from those of other aromatic compounds present to be used quantitatively.

3.3. Typical oxidation procedures

No special precautions were taken to avoid the presence of oxygen or moisture in these reactions.

Tetradecanoic acid was obtained from the oxidation of 1-pentadecene as follows. A solution consisting of 1-pentadecene (210 mg, 1.0 mmol) in acetone (10 mL) was placed in a 50 mL round bottomed flask and cooled to −78°C using a dry ice/acetone bath and stirred magnetically. $KMnO_4$ (1.6 g, 10 mmol) and $FeCl_3$ (1.0 g, 6.2 mmol) were added and after stirring for 2 h at −78°C, the flask was removed from the cooling bath and allowed to gradually warm up to room temperature (~2 h) and stirred overnight. The resulting suspension was diluted with dichloromethane (20 mL), filtered through filter paper and the residue was washed with dichloromethane (20 mL×2). The filtrate and washings were combined, dried ($MgSO_4$), decolorized (charcoal) and concentrated to give tetradecanoic acid (205 mg, 90%) as the sole product. The identity of this product was confirmed spectroscopically (^1H NMR, ^{13}C NMR and MS).

Heptanoic acid was obtained from the oxidation of 7-tetradecene as follows. A solution consisting of 7-tetradecene (197 mg, 1.0 mmol) in acetone (10 mL) was placed in a 50 mL round bottomed flask and cooled to −78°C using a dry ice/acetone bath and stirred magnetically. $KMnO_4$ (1.6 g, 10 mmol) and $FeCl_3$ (1.0 g, 6.2 mmol) were added and after stirring for 2 h at −78°C, the flask was removed from the cooling bath and allowed to gradually warm up to room temperature (~2 h) and held overnight with continuous stirring. 2-Propanol (1.5 mL) was added to reduce excess oxidant and after stirring for an additional 30 min, the suspension was diluted with dichloromethane (20 mL) and precipitated manganese dioxide was removed by filtration. The precipitate was washed in the funnel with dichloromethane (2×20 mL) and the filtrate and washings combined, dried over anhydrous magnesium sulfate, decolorized using charcoal and concentrated to give a colorless liquid that was identified to be heptanoic acid (231 mg, 1.78 mmol, 89%). The identity of this product was confirmed spectroscopically (^1H NMR, ^{13}C NMR and MS).

8,9-Dioxohexadecane was obtained from the oxidation of 8-hexadecyne as follows. A solution consisting of 8-hexadecyne (229 mg, 1.03 mmol) in acetone (10 mL) was placed in a 50 mL round bottomed flask and cooled to −78°C using a dry ice/acetone bath and stirred magnetically. $KMnO_4$ (0.80 g, 5.0 mmol) and $FeCl_3$ (0.4 g, 2.5 mmol) were added and after stirring for 80 min at −78°C, the flask was removed from the cooling bath, allowed to warm gradually to 0°C and stirred for an additional 1 h. The resulting suspension was diluted with dichloromethane (20 mL) and filtered to separate precipitated MnO_2. The precipitate was washed with dichloromethane (2×20 mL) and the filtrate and washings were combined, dried over anhydrous $MgSO_4$, decolorized with charcoal and concentrated to give a pale yellow oil that slowly solidified (238 mg, 0.937 mmol, 91%). The spectroscopic properties (^1H NMR and ^{13}C NMR) of this compound are consistent with its assigned structure and in agreement with those described in the literature.[22]

2-Nonanone was obtained from the oxidation of 2-nonanol as follows. A solution consisting of 2-nonanol (144 mg, 1.0 mmol) in acetone (10 mL) was placed in a 50 mL round bottomed flask and cooled to −78°C using a dry ice/acetone bath and stirred magnetically. $KMnO_4$ (0.8 g, 5.0 mmol) and $FeCl_3$ (0.4 g, 2.5 mmol) were added and after stirring for 2 h at −78°C, the flask was removed from the cooling bath and allowed to warm gradually to 0°C over a period of 2 h. The resulting mixture was filtered through filter paper and the residue was washed with dichloromethane (20 mL×2). The filtrate and washings were combined, dried ($MgSO_4$), decolorized (charcoal) and concentrated to give 2-nonanone (139 mg, 98%) as the sole product. The spectroscopic properties (IR, ^1H NMR and ^{13}C NMR) of this compound are consistent with its assigned structure.

2-Oxacyclohexanone was obtained from the oxidation of tetrahydropyran as follows. A solution consisting of tetrahydropyran (86 mg, 1.0 mmol) in acetone (10 mL) was placed in a 50 mL round bottomed flask and cooled to $-78°C$ using a dry ice/acetone bath and stirred magnetically. $KMnO_4$ (1.6 g, 10 mmol) and $FeCl_3$ (1.0 g, 6.2 mmol) were added and after stirring for 2 h at $-78°C$, the flask was removed from the cooling bath and allowed to warm gradually to room temperature (~2 h) and stirred for an additional 12 h. The resulting suspension was diluted with dichloromethane (20 mL), filtered through filter paper and the residue was washed with dichloromethane (20 mL×2). The filtrate and washings were combined, dried ($MgSO_4$), decolorized (charcoal) and concentrated to give 2-oxacyclohexanone (92 mg, 92 mmol, 92%) as the sole product. The spectroscopic properties (IR, MS, ^1H NMR and ^{13}C NMR) of this compound are consistent with its assigned structure.

1-Indanone was obtained from the oxidation of indane as follows. A solution consisting of indane (120 mg, 1.02 mmol) in acetone (10 mL) was placed in a 50 mL round bottomed flask and cooled to $-78°C$ using a dry ice/acetone bath and stirred magnetically. $KMnO_4$ (1.6 g, 10 mmol) and $FeCl_3$ (0.40 g, 2.5 mmol) were added and after stirring for 2 h at $-78°C$, the flask was removed from the cooling bath and allowed to warm gradually to room temperature (~2 h) and stirred for an additional 12 h. The resulting suspension was diluted with methylene chloride (20 mL), filtered and the residue was washed with dichloromethane (2×20 mL). The filtrate and washings were combined, dried over anhydrous magnesium sulfate, decolorized with charcoal and concentrated to give a pale yellow oil (128 mg, 0.97 mmol, 95%) that was identified to be indanone. The spectroscopic properties (IR, ^1H NMR and ^{13}C NMR) of this compound are consistent with its assigned structure.

Acknowledgements

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