Mechanism of C–H Bond Oxidation by a Monooxoruthenium(V) Complex†

Chi-Ming Che,* Clare Ho and Tai-Chu Lau
Department of Chemistry, University of Hong Kong, Pokfulam Road, Hong Kong

The complex $[Ru^VL(O)]^{2+}$ {HL = [2-hydroxy-2-(2-pyridyl)ethyl]bis[2-(2-pyridyl)ethyl]amine} was found to be a very active stoichiometric oxidant towards various hydrocarbons. Oxidation of alcohols was studied either in 0.1 mol dm^{-3} $HClO_4$ or CH_3CN, the observed rate law being rate = $k[Ru^V][alcohol]$. The second-order rate constants for various alcohols follow the order benzylic > secondary > primary alcohols. Kinetic isotope effects (k_H/k_D) of 5.9 and 5.3 were found for benzyl alcohol and Pr^{i}OH respectively. Similar kinetic studies for the oxidation of tetrahydrofuran gave k_H/k_D = 6.8. Stoichiometric oxidation of saturated alkanes in acetonitrile gave tertiary alcohols exclusively or ketones when only methylene groups are present. The measured k_H/k_D for the oxidation of cyclohexane determined from competitive oxidation experiments was 5.3. No cyclohexyl chloride was found when the oxidation of cyclohexane was carried out in the presence of CCl_4. The mechanism of C–H bond oxidation by Ru^V=O is discussed.

Recently the complex $[Ru^VL(O)][ClO_4]_2$ {HL = [2-hydroxy-2-(2-pyridyl)ethyl]bis[2-(2-pyridyl)ethyl]amine} was isolated.[1] The chemistry of this species is of interest for the following reasons. First, although there is an extensive oxo chemistry of ruthenium owing to the accessibility of oxidation states IV–VIII,[2] that of ruthenium(V) is relatively rare.[3,4] Secondly, because of the periodic relationship between ruthenium and iron, this complex represents a good model for Fe^V=O species, thought to play an important role in the chemistry of the cytochrome P-450 porphyrin model[5] and the Gif system.[6] Thirdly, the high redox potential of this complex ($E°$ = 1.02 V *vs.* saturated calomel electrode at pH 1 for Ru^V–Ru^{III} couple) suggests that it is a powerful oxidant. We have thus initiated a programme to examine the reactivities of $[Ru^VL(O)]^{2+}$ towards various organic and inorganic substrates. This report is concerned with the oxidation of a selection of organic compounds including alcohols, saturated hydrocarbons, aromatic hydrocarbons and cyclic ethers.

Experimental

Materials.—The complex $[Ru^VL(O)][ClO_4]_2$ was prepared as described previously.[1] Water and acetonitrile for kinetic experiments were distilled twice from alkaline permanganate, Tetrahydrofuran (thf) was purified by distillation over lithium aluminium hydride. All substrates were of reagent grade and purified by fractional distillation or recrystallization. [α,α-$^2H_2$]Benzyl alcohol was prepared by the method of Roecker and Meyer;[7] [$^2H_8$]propan-2-ol, [$^2H_8$]tetrahydrofuran and [$^2H_{12}$]cyclohexane were purchased from Aldrich Chemical Company.

Instrumentation.—Ultraviolet/visible spectra were recorded on a Shimadzu UV-240 spectrophotometer. Kinetic measurements were made using a Hi-Tech SF-51 stopped-flow module coupled with a Hi-Tech SU-40 spectrophotometer unit. The data collection process was controlled by an Apple IIe microcomputer *via* an ADS-1 interface unit, also from Hi-Tech. Organic products were analysed on a Varian 2440 gas chromatograph equipped with a flame ionization detector.

Kinetics.—Kinetic measurements were done under the condition that the concentration of organic substrate was at least in 10-fold excess of the ruthenium oxidant and were followed by monitoring the appearance of the ruthenium(III) product at 290 nm (the reaction with 4-nitrobenzyl alcohol was monitored at 365 nm). Pseudo-first-order rate constants, k_{obs}, were obtained by two-parameter (A_∞ and k_{obs}) non-linear least-squares fits of A_t *vs.* time t according to equation (1) where

$$A_t = A_\infty + (A_0 - A_\infty)\exp(-k_{obs}\,t) \qquad (1)$$

A_0 and A_∞ are the initial and final absorbances, respectively. Second-order rate constants, k_2, were obtained from linear least-square fits of k_{obs} *vs.* $[Ru^V]$.

Organic Product Analysis.—For a typical experiment, a known amount of $[Ru^VL(O)]^{2+}$ (0.01–0.02 mmol) was added to 1–2 cm^3 of solvent (0.1 mol dm^{-3} aqueous perchloric acid or acetonitrile) containing a 100-fold excess of substrate in a round-bottom flask (10 cm^3). After stirring for 5 min, internal standard was added and the product(s) was analysed by gas chromatography.

Competitive Oxidation of Cyclohexane and [$^2H_{12}$]-Cyclohexane.—The complex $[Ru^VL(O)][ClO_4]_2$ (0.017 mmol) was slowly added to a stirred solution of cyclohexane (0.3 mmol) and cyclopentane (0.3 mmol) in acetonitrile (2 cm^3). The reaction was performed in standard apparatus and the temperature was maintained at 290 K using a water-bath. Chromatographic analysis revealed two products only: cyclohexanone and cyclopentanone. A similar experiment was performed using cyclopentane (0.3 mmol) and [$^2H_{12}$]cyclohexane (0.3 mmol). The kinetic isotope effect for oxidation was calculated from equation (2). The ratio $k_{C_6D_{12}}/k_{C_5H_{10}}$ was

$$\frac{k_{C_6H_{12}}}{k_{C_5H_{10}}} = \frac{\text{area integration of } C_6H_{10}O}{\text{area integration of } C_5H_8O} \times \frac{\text{response factor of } C_6H_{10}O}{\text{response factor of } C_5H_8O} \qquad (2)$$

similarly determined. Thus k_H/k_D for the oxidation was found

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† *Non-SI units employed:* ft = 12 in = 0.3048 m, cal = 4.184 J.

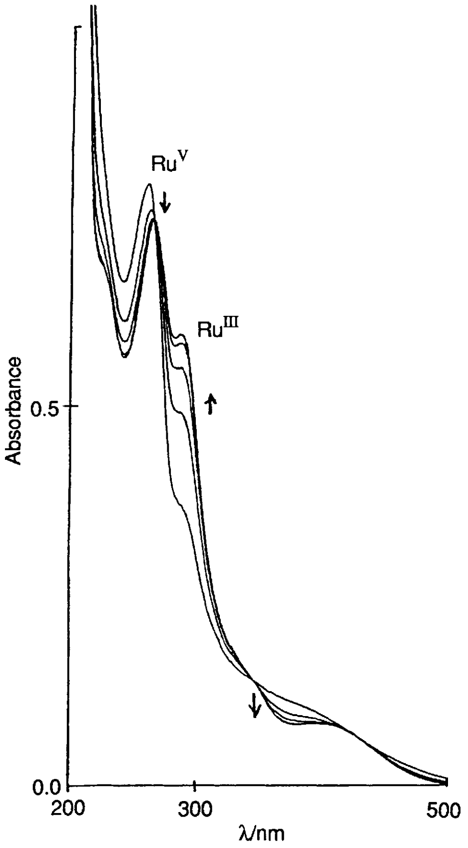


Fig. 1 Spectral changes during the oxidation of methanol (0.14 mol dm^{-3}) by [Ru^{V}L(O)]$^{2+}$ (10^{-4} mol dm^{-3}) in 0.1 mol dm^{-3} HClO$_4$. Scan interval 1 min

Table 1 Representative organic product analysis for the oxidation of hydrocarbons by [Ru^{V}L(O)]$^{2+}$

Substrate	Solvent	Product (% yield)*
Cyclobutanol	CH_3CN	Cyclobutanone (90)
Cyclohexanol	CH_3CN	Cyclohexanone (90)
4-Methylbenzyl alcohol	Water	4-Methylbenzaldehyde (90)
Tetrahydrofuran	CH_3CN	γ-Butyrolactone (80)
Cyclohexane	CH_3CN	Cyclohexanone (62)
Cyclohexane	CH_3CN–CCl_4 (9:1)	Cyclohexanone (60)
Methylcyclohexane	CH_3CN	1-Methylcyclohexanol (43)
Adamantane	CH_3CN	Adamantan-1-ol (60)
Ethylbenzene	CH_3CN	Acetophenone (95)

* Defined as the percentage of the moles of product to the moles of Ru=O oxidant.

from equation (3). The GLC conditions for this experiment

$$\frac{k_{C_6H_{12}}}{k_{C_5H_{10}}} \times \frac{k_{C_5H_{10}}}{k_{C_6D_{12}}} = k_H/k_D = 5.3 \text{ (experimental value)} \qquad (3)$$

were: 10% (w/w) Carbowax 20M on Chromosorb W (80–100 mesh, $\frac{1}{8}$ in × 6 ft stainless-steel column) with nitrogen as the carrier gas; column temperature, 110 °C; gas flow rate, 8 cm^3 min^{-1}.

Results and Discussion

Stoichiometric Oxidation.—Rapid spectrophotometric changes were observed when an excess of a primary or secondary alcohol or tetrahydrofuran was added to [Ru^{V}L(O)]$^{2+}$ in 0.1 mol dm^{-3} HClO$_4$ (Fig. 1). Examination of the final ultraviolet/visible spectrum indicated quantitative conversion of [Ru^{V}L(O)]$^{2+}$ into [Ru^{III}L(H$_2$O)]$^{2+}$ (ε_{max} = 6998 dm^3 mol^{-1} cm^{-1} at 290 nm).[1] Gas chromatographic analysis showed that an aldehyde, ketone or γ-butyrolactone was formed (Table 1). Thus the overall reaction can be represented by equations (4)–(6).

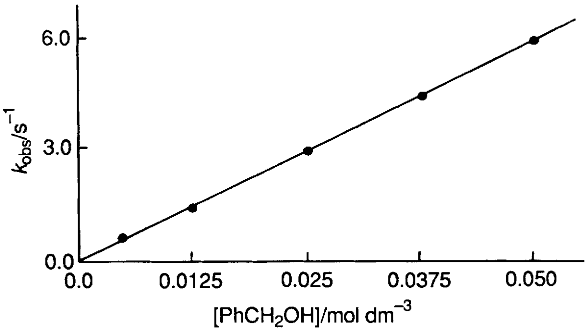
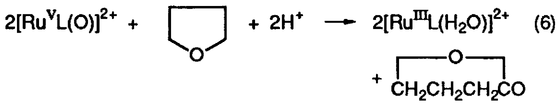


Fig. 2 Plot of k_{obs} *vs.* alcohol concentration for the oxidation of benzyl alcohol by [Ru^{V}L(O)]$^{2+}$ (10^{-4} mol dm^{-3}) in 0.1 mol dm^{-3} HClO$_4$ at 298 K

$$[Ru^VL(O)]^{2+} + RCH_2OH \longrightarrow [Ru^{III}L(H_2O)]^{2+} + RCHO \qquad (4)$$

$$[Ru^VL(O)]^{2+} + R_2CHOH \longrightarrow [Ru^{III}L(H_2O)]^{2+} + R_2C{=}O \qquad (5)$$



(6)

With saturated alkanes containing a tertiary C–H bond the complex [Ru^{V}L(O)]$^{2+}$ was found to be a selective oxidant. Only tertiary alcohols (Table 1) and no secondary or primary alcohol was detected. This is true for adamantane or methylcyclohexane with moderate yields of the corresponding tertiary alcohols (here yield is defined as the percentage of the moles of organic product formed to the moles of Ru=O oxidant). In the case of cyclohexane, cyclohexanone was found to be the only product. There was no evidence for the formation of cyclohexanol even in the early stage of the reaction. Addition of CCl$_4$ as co-solvent with acetonitrile (MeCN–CCl$_4$ 9:1) was found to have no effect on the yield of cyclohexanone (Table 1) indicating that no cyclohexyl radical was trapped in the reaction solution. The kinetic isotope effect based on the competitive oxidation of cyclohexane and [^{2}H$_{12}$]cyclohexane (see Experimental section) was found to be 5.3. This large value reflects the operation of a Ru=O···H–R intermediate with substantial C–H bond cleavage in the rate-determining step. For an aromatic hydrocarbon like ethylbenzene, the [Ru^{V}L(O)]$^{2+}$ was also very active giving acetophenone in 95% yield. Once again, no secondary alcohol was detected.

Kinetics.—The kinetics of oxidation of alcohols and tetrahydrofuran was investigated in aqueous solutions. In the presence of an excess of organic substrate, clean pseudo-first-order kinetics was found in each case. The first-order rate constants, k_{obs}, are independent of [Ru^V] but depend linearly on [substrate]. A typical plot of k_{obs} *versus* [benzyl alcohol] is shown in Fig. 2. The experimental rate law is (7). Second-order

$$\text{Rate} = k_{obs}[Ru^V] = k_2[\text{substrate}][Ru^V] \qquad (7)$$

rate constants, k_2, are collected in Table 2. For the oxidation of benzyl alcohol, the rate constants are very similar in 0.1 mol dm^{-3} HClO$_4$, 0.1 mol dm^{-3} NaClO$_4$ and CH$_3$CN. Activation parameters for benzyl alcohol, propan-2-ol and tetrahydrofuran were calculated using the Eyring plot, ln(k_2/T) *vs.* 1/*T*, over a

Table 2 Kinetic data for the oxidation of alcohols and tetrahydrofuran by $[Ru^{V}L(O)]^{2+}$ in 0.1 mol dm^{-3} $HClO_4$ at 298 K

Substrate	K_2/dm^3 mol^{-1} s^{-1}	$\Delta H^{\ddagger}$/kcal mol^{-1}	$\Delta S^{\ddagger}$/cal K^{-1} mol^{-1}
Methanol	0.07 ± 0.006^{a} 0.15 ± 0.01^{b} 0.15 ± 0.01		
Ethanol	1.7 ± 0.1		
Propan-1-ol	3.6 ± 0.4		
Propan-2-ol	13.5 ± 1.0	9.2 ± 1.0	-22 ± 2
$[^2H_8]$Propan-2-ol	2.5 ± 0.1		
Cyclohexanol	107 ± 8		
Benzyl alcohol	117 ± 5	9.1 ± 1	-18 ± 2
$[\alpha,\alpha\text{-}^2H_2]$Benzyl alcohol	20 ± 1		
4-Nitrobenzyl alcohol	32 ± 3		
4-Methylbenzyl alcohol	391 ± 22		
4-Chlorobenzyl alcohol	142 ± 10		
4-Trifluoromethylbenzyl alcohol	78 ± 7		
Tetrahydrofuran	31 ± 2	11.4 ± 1	-14 ± 2
$[^2H_8]$Tetrahydrofuran	4.6 ± 0.3		

[a] In CH_3CN. [b] In water.

temperature range of 291–312 K. The plots are shown in Fig. 3. In general, the ΔS values are large and negative (Table 2).

General Discussion.—Previous electrochemical studies[1] revealed that $[Ru^{V}L(O)]^{2+}$ can function either as a two- or a one-electron oxidant with the respective E° values being 1.02 ($Ru^{V}{=}O \longrightarrow Ru^{III}{-}OH_2$) and 0.97 V [$Ru^{V}{=}O \longrightarrow Ru^{IV}{=}O$] *vs.* saturated calomel electrode at pH 1.0. The $[Ru^{IV}{=}O]^{+}$ complex is also a powerful oxidant as suggested by its E° value of 0.76 V at pH 4.0.[1] At pH 1.0, the disproportionation reaction (8) is favoured in the forward direction by a driving

$$2[Ru^{IV}L(O)]^{+} + 2H^{+} \rightleftharpoons [Ru^{V}L(O)]^{2+} + [Ru^{III}L(H_2O)]^{2+} \quad (8)$$

force ΔG° of -11.6 kJ mol^{-1}. Based on these electrochemical data, it is not unreasonable to find that, for all of the reactions of $[Ru^{V}L(O)]^{2+}$ investigated, formation of the $[Ru^{IV}L(O)]^{+}$ intermediate was not detected, either in stopped-flow kinetic experiments or in stoichiometric oxidation reactions. The $[Ru^{V}L(O)]^{2+}$ complex functions as an overall two-electron oxidant in the oxidation of alcohols since cyclobutanol was oxidized to cyclobutanone in nearly quantitative yield (Table 1).

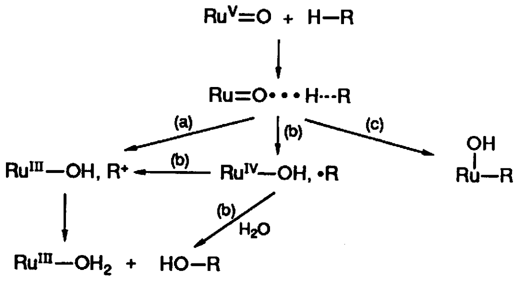
Among the Ru=O complexes known the present $[Ru^{V}L(O)]^{2+}$ is perhaps the most reactive towards C–H bond oxidation. For example, the oxidation of propan-2-ol in aqueous solution by $[Ru^{V}L(O)]^{2+}$ at 298 K (k = 13.5 dm^3 mol^{-1} s^{-1}) is faster than that by $[Ru^{IV}(bipy)_2(py)O]^{2+}$ (bipy = 2,2′-bipyridine, py = pyridine) (k = 0.067 dm^3 mol^{-1} s^{-1})[7] and RuO_4 (k = 0.016 dm^3 mol^{-1} s^{-1})[8] by factors of *ca.* 200 and 800 respectively. Furthermore, it is capable of oxidizing cyclohexane at room temperature, a property which is not shared by other Ru=O complexes.

The oxidation of alcohols, tetrahydrofuran and cyclohexane has been found to have large but similar k_H/k_D values [benzyl alcohol, 5.9 ± 0.5; propan-2-ol, 5.3 ± 0.5, tetrahydrofuran, 6.0 ± 0.7; cyclohexane, 5.3 ± 0.6]. This may reflect a common $\mathrm{Ru{=}O\cdots H{-}\overset{|}{\underset{|}{C}}{-}}$ transition state, with similar extent of C–H bond cleavage for the oxidation [equation (9)]. Such an associative mechanism is also suggested by

$$\mathrm{Ru^{V}{=}O + H{-}\overset{|}{\underset{|}{C}}{-} \longrightarrow Ru{=}O\cdots H{-}\overset{|}{\underset{|}{C}}{-}} \quad (9)$$

the measured large and negative ΔS values for the oxidation of benzyl alcohol and propan-2-ol (Table 2).

Several pathways are feasible for the C–H bond oxidation by the $Ru^{V}{=}O$ complex. These are depicted in Scheme 1. Pathways (a) and (b) are the two-electron hydride and one-electron hydrogen-atom abstraction respectively. Pathway (c) is based on Barton's work on the oxidation of hydrocarbons by the Gif system.[6] Pathway (a) has been suggested by Meyer and co-workers[7] on the oxidation of alcohols by $Ru^{IV}{-}O$. Pathway (b) is the well known 'oxygen rebound' mechanism of Groves and co-workers.[5] Mechanistically, it is difficult to distinguish between these two pathways especially in the situation where the H-atom abstraction is followed by a rapid in-cage oxygen rebound or electron transfer from $Ru^{IV}{-}OH$ to the R$^{\bullet}$ radical. Even for the alcohol oxidation, we could not make a distinction based on the present results. In this work there is no evidence for a freely diffusing R$^{\bullet}$ radical formed during the oxidation. The fact that no cyclohexyl chloride was detected in the oxidation of cyclohexane by $[Ru^{V}L(O)]^{2+}$ in the presence of CCl_4 provides support for the above statement.



Scheme 1

The oxidation of hydrocarbons by $Ru^{V}{=}O$ is likely to be facilitated by charge transfer from the C–H bond to the Ru=O oxidant. This is at least true for oxidation of alcohols. Fig. 4 shows a plot of log k_2 *versus* ionization potential for aliphatic alcohols, illustrating the linear free-energy relationship for the oxidation. Fig. 5 shows the Hammett plot for the oxidation of substituted benzyl alcohols. The data points are quite scattered. Nevertheless, if that of benzyl alcohol is neglected, a straight line could be drawn with a slope estimated to be -1.1. Such a negative ρ value is also an indication of a charge-transfer mechanism.

In this work we have always been puzzled by the observation that oxidation of cyclohexane or ethylbenzene did not give the corresponding secondary alcohol in detectable quantity. One may argue that the rate constant for the oxidation of cyclohexane could be much smaller than that for cyclohexanol so that cyclohexanol, once formed, is rapidly oxidized by $[Ru^{V}L(O)]^{2+}$ to cyclohexanone. We could not rule out this

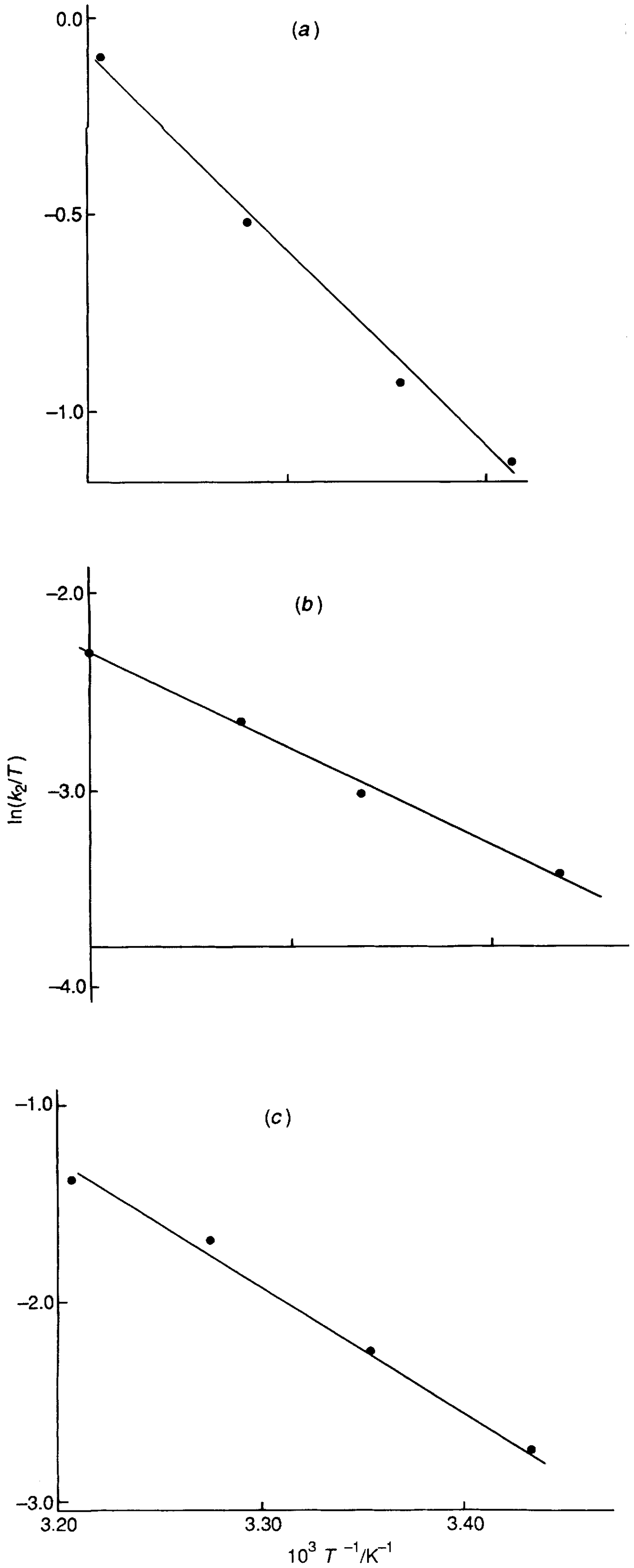


Fig. 3 Eyring plots for the oxidation of (*a*) benzyl alcohol, (*b*) propan-2-ol and (*c*) tetrahydrofuran

possibility but we do not have proof either. However, if this is the case, the two rate constants have to differ by a factor of over 10^5 in view of the large excess of cyclohexane. The selective

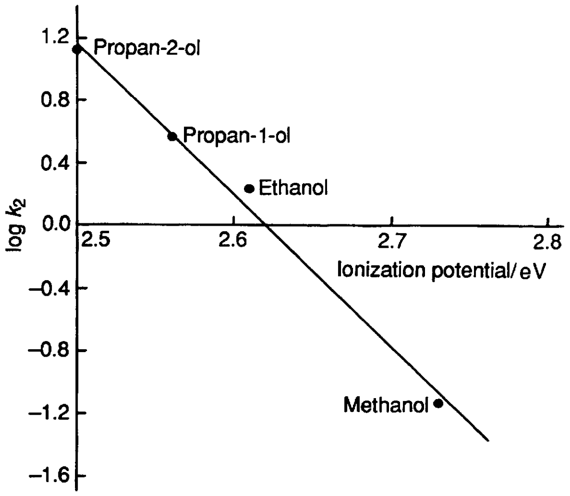


Fig. 4 Plot of log k_2 *vs.* ionization potential for aliphatic alcohols

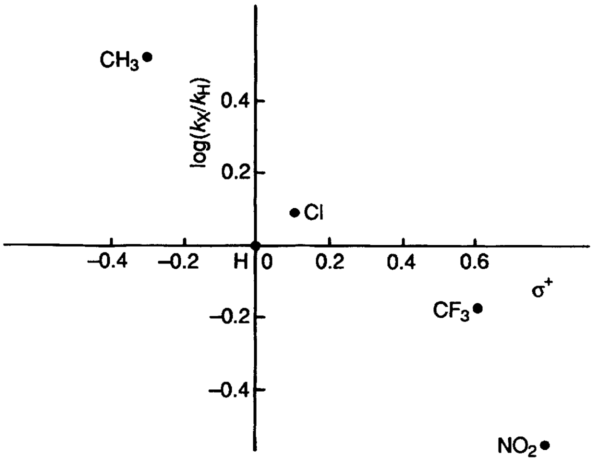


Fig. 5 Hammett plot for the oxidation of substituted benzyl alcohols (p-$XC_6H_4CH_2OH$)

formation of ketone from the oxidation of hydrocarbons containing methylene units was also reported by Barton and co-workers.[6] In the oxidation by the Gif systems, Barton proposed that the active oxidant is a $Fe^V{=}O$ species, which could react with R–H to give an unstable HO–Fe–R intermediate.[6] Such an intermediate was suggested to be responsible for the formation of a ketone instead of a secondary alcohol. If this pathway operates for the $Fe^V{=}O$ species, the reaction of the $Ru^V{=}O$ species with saturated alkanes may go through a similar mechanism.

A direct comparison between the reactivities of $[Ru^{IV}(bipy)_2(py)O]^{2+}$ and $[Ru^VL(O)]^{2+}$ reveals some important differences between the d^3- and d^4-oxo systems in alcohol oxidation. The $[Ru^{IV}(bipy)_2(py)O]^{2+}$ complex is a d^4-monooxo system, and hence its reactions with alcohols to give Ru^{II} involve a spin change at ruthenium. In the $[Ru^VL(O)]^{2+}$ system the corresponding reactions are spin-allowed processes since both the $Ru^V{=}O$ and $Ru^{III}{-}OH_2$ species have similar μ_{eff} values.[1] This implies that, if other factors are the same, Ru^V should be more reactive than Ru^{IV} due to the lack of a spin barrier in the former system. A notable difference between the two systems is the kinetic isotope effect in the oxidation of benzyl alcohol. The measured kinetic isotope effect of 5.9 ± 0.5 for Ru^V, though substantial, is much smaller than the value of 50 obtained using $[Ru^{IV}(bipy)_2(py)O]^{2+}$ as oxidant.[7] Furthermore, this value is close to that of 5.3 ± 0.5 for the oxidation of propan-2-ol, in contrast to the work by Meyer and co-workers[7] who reported that the k_H/k_D values for benzyl alcohol and propan-2-ol ultilizing $[Ru^{IV}(bipy)_2(py)O]^{2+}$ as oxidant are 50 and 18 respectively. It appears that the extent of interaction of the α(C–H) bond of the alcohol with the Ru=O moiety in the transition state, as reflected by the kinetic isotope effect, may also be sensitive to the electronic state of the Ru=O oxidant.

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