

# The Mechanism of RuO<sub>4</sub>-Mediated Oxidations of Saturated Hydrocarbons. Reactivity, Kinetic Isotope Effect and Activation Parameters

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The mechanism of the RuO<sub>4</sub>-mediated oxidations of saturated hydrocarbons have been studied by a kinetic investigation of the oxidation of *cis*-decalin (**1**), *trans*-decalin (**2**), *cis*-1,2-dimethylcyclohexane (**3**), *trans*-1,2-dimethylcyclohexane (**4**), *endo*-tricyclo[5.2.1.0<sup>2,6</sup>]decane (**5**), adamantane (**6**) and perdeuterio-*cis*-decalin (**1-d<sub>18</sub>**). The results could be divided into the reactivity of secondary and tertiary axial and equatorial hydrogen atoms. Second-order rate coefficients ( $k_2/10^{-4} \text{ M}^{-1} \text{ s}^{-1}$ ) at 30°C are: equatorial tertiary 4.0; axial tertiary 0.42; equatorial secondary 0.085; axial secondary 0.009. From the rates of *cis*-decalin and perdeuterio-*cis*-decalin  $k_H/k_D = 4.8$  was obtained. It is proposed that the reaction proceeds either *via* a carbocation–perruthenate ion-pair or by a highly polar cyclic transition state with the ion-pair route as a minor, competing pathway.

Dedicated to Professor Lars Skattebøl on the occasion of his 65th birthday.

The selective derivatisation of saturated hydrocarbons continues to attract interest from both a preparative and theoretical viewpoint.<sup>1</sup> The need for specific derivatisation of non-activated hydrocarbons is obvious. From a theoretical point, interest stems both for such reactions to act as biological mimics<sup>2–4</sup> and from a wish to understand the detailed mechanism of these reactions.<sup>5–7</sup>

We have previously studied the RuO<sub>4</sub>-mediated oxidation of saturated hydrocarbons by NaIO<sub>4</sub> from both a preparative<sup>8</sup> and mechanistic standpoint.<sup>9</sup> It was shown that the reaction did not proceed by a one-electron transfer or by a hydrogen-atom abstraction in the rate-determining step but that a hydride abstraction appeared to be the preferred pathway.<sup>9</sup> Tenaglia *et al.* have proposed that the reaction proceeds by an insertion reaction on the C–H bond, perhaps with development of a positive charge on the carbon atom in the transition state (TS).<sup>10</sup>

By comparing the reactivity of a range of hydrocarbons we hoped to gain further information on the details of the reaction mechanism and we now report a detailed kinetic study of this reaction.

## Results

An early aim of this investigation was to study the ruthenium tetraoxide mediated oxidation of the stereoisomeric 1,2-dimethylcyclohexyl acetates. The hydride-transfer mechanism, if correct, was expected to lead to neighbouring-group participation by the axial acetoxy group in *trans*-1,2-dimethylcyclohexyl acetate on oxidation of the

vicinal axial tertiary C–H bond, but to little or no participation in the related *cis*-ester in which the acetoxy group occupies an equatorial location, preventing rearside access to a developing positive charge. In the event, both compounds proved to be perfectly inert, and not only in the 2-position. This was also the case with *cis*- and *trans*-2-methylcyclohexyl acetates. This made possible the use of these compounds as internal standards in the gas chromatographic analyses used in the kinetic investigation. It was established, by comparison of oxidations followed with such an internal standard and using an external standard (*t*-butylbenzene), that the presence of the acetates had no significant effect on the rate of oxidation of the substrate.

**Kinetic form.** Kinetic results for the ruthenium tetraoxide mediated oxidation of *cis*-decalin **1** over a range of ruthenium tetraoxide concentrations and temperatures are in Table 1, and these serve to demonstrate that the observed first-order rate coefficients,  $k_{\text{obs}}$ , for the disappearance of the hydrocarbon increase in proportion to [RuO<sub>4</sub>]. Accordingly, observed rate coefficients were transformed into second-order rate constants  $k_2 (= k_{\text{obs}}/[\text{RuO}_4])$  for all substrates, *cis*-decalin (**1**, Table 1), *trans*-decalin (**2**, Table 2), *cis*-1,2-dimethylcyclohexane (**3**, Table 3), *trans*-1,2-dimethylcyclohexane (**4**, Table 4), *endo*-tricyclo[5.2.1.0<sup>2,6</sup>]decane (**5**, Table 5) and adamantane (**6**, Table 6). In Table 7 are given results for the oxidation of perdeuterio-*cis*-decalin (**1-d<sub>18</sub>**) under similar conditions. For each substrate, activation parameters were determined using a linear regression program, and the results, including correlation coefficients and standard deviations are listed in Table 8.

**Table 1.** Kinetics of oxidation of *cis*-decalin (**1**) by sodium periodate mediated by ruthenium tetroxide in CCl<sub>4</sub>-CH<sub>3</sub>CN-H<sub>2</sub>O (2:1:2).

θ/°C	[RuO <sub>4</sub> ]/mM	k <sub>obs</sub> /10 <sup>-5</sup> s <sup>-1</sup>	k <sub>2</sub> /10 <sup>-4</sup> M <sup>-1</sup> s <sup>-1</sup>
2.4	24.4	0.16(1)	0.66(6)
30.0	4.6	0.35(2)	7.6(4)
	4.6	0.345(9)	7.3(2)
	9.7	0.792(4)	8.16(4)
47.8	18.9	1.54(6)	8.2(3)
	19.6	6.9(1)	35.2(5)

**Table 2.** Kinetics of oxidation of *trans*-decalin (**2**) by sodium periodate mediated by ruthenium tetroxide in CCl<sub>4</sub>-CH<sub>3</sub>CN-H<sub>2</sub>O (2:1:2).

θ/°C	[RuO <sub>4</sub> ]/mM	k <sub>obs</sub> /10 <sup>-5</sup> s <sup>-1</sup>	k <sub>2</sub> /10 <sup>-4</sup> M <sup>-1</sup> s <sup>-1</sup>
2.4	20.3	0.021(4) <sup>a</sup>	0.10(2)
	24.4	0.025(7) <sup>b</sup>	0.10(3)
9.9	23.4	0.040(4) <sup>c</sup>	0.17(2)
21.0	26.3	0.14(1)	0.51(4)
30.0	19.3	0.305(8)	1.58(5)
32.5	13.1	0.255(7)	1.95(5)
46.5	20.3	1.77(3)	8.7(1)
47.8	19.6	1.13(2)	5.78(8)

<sup>a</sup>Correlation coefficient 0.937; <sup>b</sup>C.c. 0.985; <sup>c</sup>C.c. 0.981.**Table 3.** Kinetics of oxidation of *cis*-1,2-dimethylcyclohexane (**3**) by sodium periodate mediated by ruthenium tetroxide in CCl<sub>4</sub>-CH<sub>3</sub>CN-H<sub>2</sub>O (2:1:2).

θ/°C	[RuO <sub>4</sub> ]/mM	k <sub>obs</sub> /10 <sup>-5</sup> s <sup>-1</sup>	k <sub>2</sub> /10 <sup>-4</sup> M <sup>-1</sup> s <sup>-1</sup>
2.4	20.3	0.076(4)	0.38(2)
9.9	24.3	0.165(6)	0.68(2)
	25.4	0.165(6)	0.65(2)
30.0	21.7	1.04(2)	4.80(7)
32.5	13.1	0.85(2)	6.5(2)
40.0	22.9	2.6(1)	11.2(6)
46.5	20.0	3.88(7)	19.4(4)
50.0	20.3	4.85(6)	23.9(3)
	23.2	5.4(2)	23.2(6)

**Table 4.** Kinetics of oxidation of *trans*-1,2-dimethylcyclohexane (**4**) by sodium periodate mediated by ruthenium tetroxide in CCl<sub>4</sub>-CH<sub>3</sub>CN-H<sub>2</sub>O (2:1:2).

θ/°C	[RuO <sub>4</sub> ]/mM	k <sub>obs</sub> /10 <sup>-5</sup> s <sup>-1</sup>	k <sub>2</sub> /10 <sup>-4</sup> M <sup>-1</sup> s <sup>-1</sup>
9.9	23.4	0.032(6)	0.14(2)
30.0	21.7	0.200(7)	0.92(3)
32.5	13.1	0.172(8)	1.31(5)
40.0	22.9	0.8(1) <sup>a</sup>	3.6(6)
46.5	20.0	0.70(3)	3.5(1)
50.0	23.2	1.19(3)	5.1(1)

<sup>a</sup>C.c. 0.938.**Table 5.** Kinetics of oxidation of tricyclo[5.2.10<sup>2.6</sup>]decane (**5**) by sodium periodate mediated by ruthenium tetroxide in CCl<sub>4</sub>-CH<sub>3</sub>CN-H<sub>2</sub>O (2:1:2).

θ/°C	[RuO <sub>4</sub> ]/mM	k <sub>obs</sub> /10 <sup>-5</sup> s <sup>-1</sup>	k <sub>2</sub> /10 <sup>-4</sup> M <sup>-1</sup> s <sup>-1</sup>
2.4	24.4	0.22(2)	0.88(7)
30.0	19.3	2.40(1)	12.4(4)
47.8	19.6	8.5(1)	43.5(7)

**Table 6.** Kinetics of oxidation of adamantane (**6**) by sodium periodate mediated by ruthenium tetroxide in CCl<sub>4</sub>-CH<sub>3</sub>CN-H<sub>2</sub>O (2:1:2).

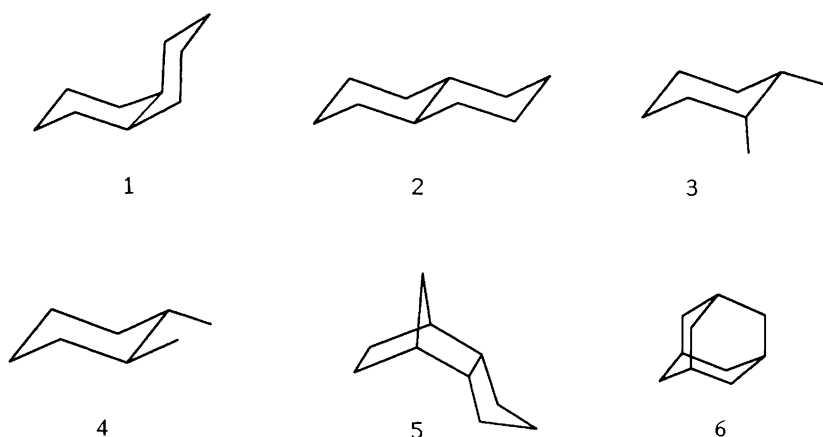
θ/°C	[RuO <sub>4</sub> ]/mM	k <sub>obs</sub> /10 <sup>-5</sup> s <sup>-1</sup>	k <sub>2</sub> /10 <sup>-4</sup> M <sup>-1</sup> s <sup>-1</sup>
9.9	23.4	0.56(1)	2.39(4)
32.5	13.1	2.59(4)	19.8(3)
46.0	19.3	10.06(1)	52.1(1)

**Table 7.** Kinetics of oxidation of perdeuterio-*cis*-decalin by sodium periodate mediated by ruthenium tetroxide in CCl<sub>4</sub>-CH<sub>3</sub>CN-H<sub>2</sub>O (2:1:2).

θ/°C	[RuO <sub>4</sub> ]/mM	k <sub>obs</sub> /10 <sup>-5</sup> s <sup>-1</sup>	k <sub>2</sub> /10 <sup>-4</sup> M <sup>-1</sup> s <sup>-1</sup>
9.9	25.4	0.058(3)	0.23(1)
30.0	21.7	0.377(8)	1.74(4)
40.0	22.9	0.84(1)	3.67(6)
50.0	23.2	2.29(2)	9.9(1)

**Table 8.** Arrhenius parameters and entropy of activation at 303.2 K for oxidations mediated by ruthenium tetroxide in CCl<sub>4</sub>-CH<sub>3</sub>CN-H<sub>2</sub>O (2:1:2).

Compound	log A	E <sub>a</sub> /kcal mol <sup>-1</sup>	n	Correlation <sup>a</sup> Coefficient	ΔS <sup>‡</sup> /cal K <sup>-1</sup> mol <sup>-1</sup>
<b>1</b>	7.9(3)	15.3(4)	6	0.9988	-26.2
<b>1-d<sub>18</sub></b>	8.4(4)	16.8(5)	4	0.9990	-24.3
<b>2</b>	9.3(6)	16.9(8)	8	0.9941	-24.3
<b>3</b>	8.4(3)	16.2(5)	9	0.9981	-24.2
<b>4</b>	7.7(3)	16.2(5)	5	0.9988	-27.5
<b>5</b>	8.0(4)	15.2(6)	3	0.9993	-25.9
<b>6</b>	8.3(4)	15.4(6)	3	0.9994	-24.6



**Reaction products.** With the exception of compounds **2** and **5**, all substrates gave a single primary product on oxidation, namely, the corresponding tertiary alcohol. In the case of the reaction of **3** which was >99% pure, only a single isomer of 1,2-dimethylcyclohexanol was produced and this was shown by comparison of the GC retention time with those of authentic samples to be the *cis*-isomer, i.e., the product of C–H oxidation with retention of configuration.

It was noted that in some instances, for example the oxidation of **3**, that the initially formed alcohol was itself slowly oxidised under the reaction conditions so that the yield of alcohol declined steadily with conversion after about two half-lives of the substrate. For the substrates **1**, **4** and **6**, the fraction of reaction taking place at equivalent tertiary C–H centres ( $F$ ) was taken to be unity. A previously determined value of  $F$  of 0.92 was used for **5**.<sup>9</sup> In the case of *trans*-decalin,  $F$  was determined experimentally from the initial rate of appearance (GC) of *trans*-9-decalol compared with that of the 1- and 2-*trans*-decalones, the other initial products of oxidation resulting from attack at secondary C–H centres. The observed values showed no trend with temperature over the range 2.4 to 46.5 °C, implying very similar activation parameters for attack at all positions. Values were therefore averaged, giving  $F = 0.50$  (tertiary), 0.24 (1-position) and 0.26 (2-position). Table 9

gives values of  $k_2$  calculated for 30 °C from the activation parameters in Table 8, together with reactivities per tertiary C–H bond ( $=k_2F/\sigma$ , where  $\sigma$  is the number of equivalent tertiary C–H bonds in the substrate molecule). Corrected entropies of activation are also included.

For *cis*-1,2-dimethylcyclohexane (**3**), the tertiary C–H bonds are not equivalent, one being axial and one equatorial. The value of  $k_2F/\sigma$  is formally  $2.44 \times 10^{-4} \text{ M}^{-1} \text{ s}^{-1}$ , but the total reactivity can be divided into separate contributions from the axial and equatorial C–H bonds by assuming that the axial reactivity (from the reactivity of the *trans*-isomer) is unchanged in the *cis*-compound. The reactivity of the equatorial C–H then turns out to be some 9.4 times higher than for the axial.

**Kinetic deuterium isotope effect.** Direct kinetic measurements on *cis*-decalin and its perdeuterio-analogue showed a large kinetic isotope effect, (KIE) 4.8 at 30 °C. This value is similar in magnitude to that obtained previously from product studies on the oxidation of **5** at room temperature.<sup>9</sup> In the present instance, however, the observed value is modified to an unknown degree by secondary ( $\beta$ ) isotope effects of five deuterium atoms in positions vicinal to the tertiary sites undergoing oxidation. A principal concern of the study was to investigate whether the large KIE in ruthe-

Table 9. Comparison of reactivities per tertiary hydrogen in oxidations mediated by ruthenium tetroxide in  $\text{CCl}_4\text{-CH}_3\text{CN-H}_2\text{O}$  (2:1:2) at 30 °C.

Compound	$k_2/10^{-4} \text{ M}^{-1} \text{ s}^{-1}$	$F/\sigma$	$(k_2F/10^{-4} \sigma)/\text{M}^{-1} \text{ s}^{-1}$	$\Delta S^\ddagger/\text{cal K}^{-1} \text{ mol}^{-1}$
<b>1</b>	7.93	0.500	3.97	–27.6
1- $d_{18}$	1.64	0.500	0.82	–25.7
<b>2</b>	1.49	0.2485	0.370	–27.1
<b>3</b>	4.87	0.500	2.44 (eq. 4.40, ax. 0.47)	–25.6 <sup>a</sup>
<b>4</b>	0.933 <sup>b</sup>	0.500	0.467 <sup>b</sup>	–28.8
<b>5</b>	11.22	0.460	5.16	–27.5
<b>6</b>	14.85	0.250	3.71	–27.3

<sup>a</sup>Assuming additivity, values are –24.4 (equatorial H); –28.8 (axial H).

<sup>b</sup>For methylcyclohexane, the direct observed value is 1.2 (one axial bond).

nium tetraoxide oxidations of hydrocarbons might result from quantum-mechanical tunnelling. The observed KIE did indeed show substantial variation over the temperature range studied, giving values of 5.8 at 10 °C and 4.1 at 50 °C, arising from changes in activation parameters somewhat larger than expected on the basis of loss of the zero-point energy of the C–H stretching vibration.

## Discussion

**Reactivity.** The substrates examined in this investigation embrace an overall reactivity range of about fifteenfold. The kinetic form, rate dependence on substrate structure, the magnitude of the activation parameters and the observation of substantial KIE all indicate that the measured rates are of a process in which substrate and oxidant interact with cleavage of the C–H bond; transport within the two-phase reaction medium is not a factor.

The three most reactive substrates, **1**, **5** and **6** show remarkably similar activation parameters, especially when considered on a 'per tertiary C–H bond' basis. More revealing is the comparison of compounds **2** and **4** with **6**. Both *trans*-decalin and *trans*-1,2-dimethylcyclohexane have two axial tertiary C–H bonds; adamantane has four equatorial C–H bonds. Tables 8 and 9 reveal that the lower reactivity of **2** and **4** stems largely from the increased activation energy consistent with substantial steric determination of reactivity. Combining the reactivity data from these three compounds with that for *cis*-1,2-dimethylcyclohexane divided into axial and equatorial contributions as described above, reveals a consistent pattern of reactivity for equatorial and axial C–H bonds. This can be extended to secondary C–H bonds using the product data obtained from *trans*-decalin oxidation, assuming that the relative reactivity of equatorial to axial C–H is 9.4 as found from the treatment of the 1,2-dimethylcyclohexanes. Approximate second-order rate coefficients ( $k_2/10^{-4} \text{ M}^{-1} \text{ s}^{-1}$ ) at 30 °C are then as follows: equatorial tertiary 4.0; axial tertiary 0.42; equatorial secondary 0.085; axial secondary 0.009. On this basis the predicted value of  $k_2$  for methylcyclohexane at 30 °C is  $0.9 \times 10^{-4}$ ; (1 axial tertiary, 5 equatorial and 5 axial secondary), the value observed is  $1.2 \times 10^{-4} \text{ m}^{-1} \text{ s}^{-1}$  indicating a remarkable level of agreement, bearing in mind the approximations.

**Kinetic deuterium isotope effect.** The observations with perdeuterio-*cis*-decalin confirm the earlier finding that ruthenium tetraoxide oxidation of tertiary C–H bonds is associated with isotope effects much larger than those found for comparable oxidations by peracids (2.2 at 60 °C for methylcyclohexane)<sup>5</sup> and by methyl(trifluoromethyl)dioxirane (1.95 at –3.9 °C for cyclohexane).<sup>11</sup> The mechanistic significance of this difference in behaviour depends on whether the value observed with ruthenium tetraoxide is enhanced as a result of quantum mechanical tunnelling, and our results offer some information on this. In addition, the contribu-

tion of secondary ( $\beta$ ) deuterium isotope effects needs to be assessed.

Two limiting models can be considered for the TS: a synchronous reaction and a reaction *via* an intermediate free carbenium ion. In the first case, only small  $\beta$ -secondary deuterium isotope effects would be expected and  $(k_H/k_D)_{\text{primary}} = \text{ca. } 4$ .<sup>12,13</sup> In the second case, a substantial part of the observed isotope effect could be secondary. Ignoring the conformational dependence of  $\beta$ -effects and assuming an average rate retardation of 20 %, <sup>12,13</sup> leads to a maximum predicted  $(k_H/k_D)_{\beta}$  for five vicinal deuterium atoms in  $(1-d_{18})$  of  $1.2^5 = \text{ca. } 2.5$ . This would mean that  $(k_H/k_D)_{\text{primary}} = \text{ca. } 2.0$  at 30 °C. It is evident, therefore, that with both limiting models,  $(k_H/k_D)_{\text{primary}}$  is larger than the values observed in comparable hydrocarbon oxidations, such as those mediated by dioxiranes,<sup>11</sup> and is in the range of values associated with hydride transfer.<sup>14</sup>

Comparison of the activation parameters in Table 8 for **1** and its perdeuterio-analogue reveals that  $\Delta E_a = 1.53 \text{ kcal mol}^{-1}$  and  $A_D/A_H = 2.6$ . Both of these values are somewhat larger than predicted on the basis of loss of zero-point vibration energy of C–H stretching in the substrate ( $\Delta E_a = 1.2 \text{ kcal mol}^{-1}$ ;  $A_D/A_H = 1$ ).<sup>15</sup> Bearing in mind the uncertainties in the observed activation parameters, however, it is probable that the tunnelling correction could be fairly small. It is worth noting that very similar  $\Delta E_a$  and  $A_D/A_H$  values have been found in permanganate oxidations of 2,2,2-trifluoro-1-phenylethanol,<sup>16</sup> and 2,2,2-trifluoroacetaldehyde hydrate in aqueous solution.<sup>17</sup>

Accordingly, in assessing the mechanism of ruthenium tetraoxide oxidation of hydrocarbons, the existence of a substantial primary deuterium isotope effect must be taken into account.

**Mechanism.** Of the possible mechanisms of oxidation of hydrocarbons by ruthenium tetraoxide we consider here only the polar (hydride transfer) mechanism; arguments against mechanisms involving odd-electron species (radicals, radical ions) have already been presented.<sup>9</sup> The mechanistic question thus becomes one of distinguishing a stepwise pathway by way of a discrete intermediate carbenium ion (two TS) from a concerted process involving a single TS, see Scheme 1. The available evidence may be summarized as follows.

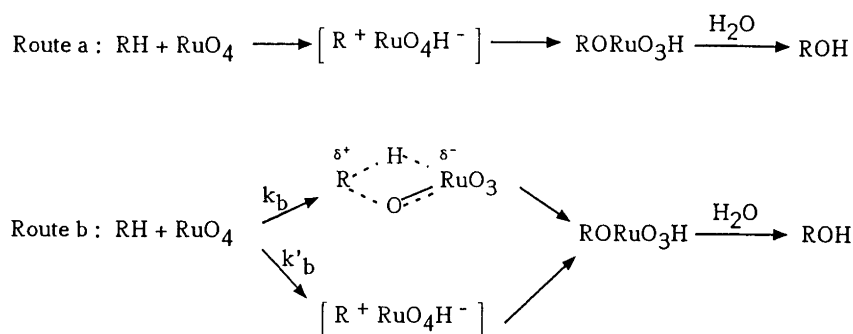
(i) The reaction is kinetically second order with rather low activation enthalpy (14–16 kcal mol<sup>-1</sup>) and large negative activation entropy (typically –27 cal K<sup>-1</sup> mol<sup>-1</sup> on a per C–H bond basis at 303 K).

(ii) The reaction shows a primary kinetic deuterium isotope effect,  $\geq 2$ , when corrections are made for secondary isotope effects and quantum mechanical tunnelling.

(iii) The reactivity of C–H bonds decreases in the sequence tertiary > secondary  $\gg$  primary and the reaction is subject to steric effects (equatorial reacts faster than axial).

(iv) The oxidation takes place with retention of configuration.

To this evidence can be added the observations (i) no



Scheme 1.

skeletal (Wagner–Meerwein) rearrangement in the oxidation of hydrocarbons of bridged polycyclic hydrocarbons described by Tenaglia *et al.*,<sup>10</sup> and (ii) the production of chloroalkanes during ruthenium tetraoxide ( $\text{RCI}/\text{ROH}$  1/10 for **5** and **1**) oxidation in the presence of chloride ion.<sup>9,18</sup>

The magnitude of the activation parameters does not allow a clear-cut mechanistic distinction. Based on NMR line-broadening studies, Brownstein and Bernais obtained  $E_a = 3.6 \text{ kcal mol}^{-1}$  and  $\Delta S^\ddagger = -27 \text{ cal K}^{-1} \text{ mol}^{-1}$  for hydride transfer from isobutane to *t*-butyl cation in  $\text{SO}_2$  solution.<sup>20</sup> The value of  $\Delta S^\ddagger$  is essentially identical with the values observed in the present investigation. For comparison,  $\Delta S^\ddagger$  calculated at  $-23.9^\circ\text{C}$  for the oxidation of cyclohexane by methyl(trifluoromethyl)dioxirane, which is arguably a concerted process,<sup>11</sup> is  $-17 \text{ cal K}^{-1} \text{ mol}^{-1}$ . For methylcyclohexane oxidation by 4-nitroperbenzoic acid at  $60^\circ\text{C}$ ,  $\Delta S^\ddagger = -29 \text{ cal K}^{-1} \text{ mol}^{-1}$ .<sup>5</sup>

In attempting to interpret the available evidence on the ruthenium tetraoxide mediated oxidation of aliphatic hydrocarbons, we are conscious of the consideration, so forcefully put by Jencks,<sup>20</sup> of the probable lifetime of putative intermediates under the reaction conditions. We will thus attempt to distinguish between an ion-pair with a short but distinct lifetime and a concerted process. The stepwise pathway is only feasible if the carbocation intermediate, whether as a free ion or, as is more likely in tetrachloromethane solution, an association complex with the perruthenate counter ion, has a lifetime significantly longer than the vibrational period of the C–O bond ( $10^{-13} \text{ s}$ ). The only experimental evidence that bears directly on this is the observation of trapping by chloride ion in the oxidation of **5**;<sup>9</sup> similar observations have also been made using **1**, the product being a 1:1 mixture of *cis* and *trans* 9-chlorodecalin.<sup>18</sup> In neither case does it appear possible that the chlorinated product arose by displacement of perruthenate from the initial oxidation product. It would seem, therefore, that an intermediate with carbocation character capable of being partitioned between available nucleophiles is generated in some measure at least.

From this evidence, it seems unlikely that the oxidation takes place by a synchronous concerted four- or five-membered cyclic mechanism. Owing to the non-linearity of the transition state, a small isotope effect would have been

expected; we observed  $k_H/k_D = \text{ca. } 4.8$ . On the other hand, a mechanism by way of a free carbocation also appears to be excluded; in the absence of added nucleophiles, complete retention of configuration was observed. Furthermore, no rearrangements were observed in bicyclic systems.<sup>10</sup>

The evidence can, however, be explained by a model in which a carbocation is formed with concomitant formation of a nucleophilic  $\text{HRuO}_4^-$  species adjacent to the carbocation. Under normal reaction conditions (non-polar solvent, no external nucleophiles present) the ion pair collapses to the ruthenate ester which eventually is hydrolysed to the alcohol. In the presence of chloride ion, reaction of the ion-pair with these competes with the collapse of the ion-pair and alkyl chlorides are formed with both retention and inversion of configuration (route a in Scheme 1).<sup>18</sup> The absence of inversion when no chloride is added indicates that collapse of the ion-pair is much faster than migration of the perruthenate ion from one face of the carbenium ion species to the other.

A mechanism with two competing pathways can, however, not be excluded: one *via* a cyclic TS with a well developed positive charge on the carbon atom and one *via* a more high-energy TS to form an ion-pair ( $k_b \gg k'_b$ , Scheme 1). This is detected on addition of chloride ions (route b, Scheme 1). However, with a non-linear TS for the major pathway one would expect a smaller KIE than that found both in this report and earlier.<sup>9</sup>

## Experimental

**Materials.** Solvents were the purest available commercial grade and were used without additional purification. Similarly the substrates were also commercial samples of 99% purity or greater as judged by analytical gas chromatography. 2-Methylcyclohexyl acetate and 1,2-dimethylcyclohexyl acetates, which were used as internal standards in GLC analyses, were prepared as a mixture of diastereoisomers by acetylation of samples of the corresponding alcohols using the procedure of Nevitt and Hammond;<sup>21</sup> the former had b.p.  $65\text{--}66^\circ\text{C}/10 \text{ mmHg}$  and was shown by <sup>1</sup>H NMR spectroscopy to consist of a 2.4:1 mixture of *trans*- and *cis*-isomers, while the latter had b.p.  $70\text{--}72^\circ\text{C}/10$

mmHg and was a 3.7:1 mixture (by GLC) of the isomers having their methyl groups *trans* and *cis*.

**Kinetic experiments.** These were carried out in a three-necked, round-bottomed flask of 100 cm<sup>3</sup> capacity, equipped with a magnetic stirrer bar and maintained at constant temperature by circulating fluid from a thermostat through an external jacket. Reaction mixtures were prepared from sodium periodate (2.06 g), distilled water (20 cm<sup>3</sup>), acetonitrile (10 cm<sup>3</sup>) and tetrachloromethane (20 cm<sup>3</sup>). Measurements showed that such mixtures separated into two layers each having a volume of 25 cm<sup>3</sup>. To this mixture was added a weighed amount of ruthenium dioxide, typically in the range 20 to 80 mg, actual concentrations in the organic layer being determined from a calibration chart constructed from spectrophotometric measurements of the absorbance of such solutions at 385 nm and using Connick and Hurley's<sup>22</sup> value for the extinction coefficient of ruthenium tetraoxide. By measuring the absorbance of both phases in reaction mixtures, it was found that the distribution coefficient of ruthenium tetraoxide between tetrachloromethane and aqueous sodium periodate in the presence of acetonitrile at 30 °C is 28 compared with a value of 58 reported<sup>23</sup> for the distribution between pure tetrachloromethane and water.

Reactions were initiated by the addition of the substrates for oxidation (1 mmol), together with the internal standard, usually as a solution in a portion of the tetrachloromethane; typically three substrates were studied together in each kinetic run. The two-phase mixture was stirred vigorously throughout the course of the reaction; in this way, reaction mixtures retained the clear lemon yellow colour of ruthenium tetraoxide, with no trace of the black dioxide. With the large excess of the primary oxidant, sodium periodate, the ruthenium tetraoxide concentration in the organic phase remained constant throughout the reaction, fulfilling an essential catalytic role. Samples of the reaction mixture (0.40 cm<sup>3</sup>) were withdrawn by pipette at intervals and quenched in a mixture of 2-propanol (1 cm<sup>3</sup>) in water (ca. 3 cm<sup>3</sup>). This procedure led to the conversion of ruthenium tetraoxide into the insoluble dioxide. When necessary, an external standard (*t*-butylbenzene) was added at this point. Extraction of the quenched sample with diethyl ether gave a solution which was analysed by GLC (capillary column, Carlo Erba CB-1, non-polar 30 m × 0.32 mm; the temperature programme, 50 °C × 5 min, then 10 °C min<sup>-1</sup> to 250 °C).

The GLC responses of the substrates decayed with time according to a first-order kinetic law over two or more

half-lives. Rate coefficients were evaluated by least squares, correlation coefficients for the linear regression being in every case greater than 0.99. The reproducibility was normally within ±5 % of the mean value.

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## References

- Mello, R., Fiorentio, M., Fusco, C. and Curci, R. *J. Am. Chem. Soc.* **111** (1989) 6749 and references cited therein.
- Groves, J. T. and Nemo, T. E. *J. Am. Chem. Soc.* **105** (1983) 6243.
- Lindsay-Smith, J. R. and Sleath, P. R. *J. Chem. Soc., Perkin Trans. 2* (1983) 1165.
- Mansuy, D. *Pure Appl. Chem.* **59** (1987) 759.
- Schneider, H. J. and Muller, W. J. *J. Org. Chem.* **50** (1985) 409.
- Scheldon, R. A. In: Kochi, J. K., Ed., *Metal-Catalyzed Oxidations of Organic Compounds*, Academic Press, New York 1981.
- Bailey, P. S. *Ozonisation in Organic Chemistry*, Academic Press, New York 1982.
- Bakke, J. M. and Lundquist, M. *Acta Chem. Scand., Ser. B* **40** (1986) 430.
- Bakke, J. M. and Bränden, J. E. *Acta Chem. Scand.* **45** (1991) 418.
- Tenaglia, A., Terranova, E. and Waegell, B. *Tetrahedron Lett.* **30** (1989) 5271; Tenaglia, A., Terranova, E. and Waegell, B. *J. Chem. Soc., Chem. Commun.* 1990, 1344.
- Mello, R., Fiorentino, M., Fusco, C. and Curci, R. *J. Am. Chem. Soc.* **111** (1989) 6749; see also Murray, R. W., Jeyaraman, R. and Mohan, L. *J. Am. Chem. Soc.* **108** (1986) 2470.
- Sunko, D. E. and Hehre, W. J. *Prog. Phys. Org. Chem.* **14** (1983) 205.
- Halevi, E. A. *Prog. Phys. Org. Chem.* **1** (1968) 109.
- Watt, C. I. F. *Adv. Phys. Org. Chem.* **24** (1988) 57.
- Bell, R. P. *The Tunnel Effect in Chemistry*, Chapman and Hall, London, 1980.
- Lewis, E. S. and Robinson, J. K. *J. Am. Chem. Soc.* **90** (1968) 4337; Stewart, R. and van der Linden, R. *Discuss. Faraday Soc.* **29** (1960) 211.
- Stewart, R. and Mocek, M. M. *Can. J. Chem.* **41** (1963) 1161.
- Frøhaug, A. and Bakke, J. M. *Unpublished results*.
- Brownstein, S. and Bornais, J. *Can. J. Chem.* **49** (1971) 7.
- Jencks, W. P. *Chem. Soc. Rev.* **10** (1981) 345. For a recent application of these ideas, see Amyes, T. L. and Richard, J. P. *J. Am. Chem. Soc.* **112** (1990) 9507.
- Nevitt, T. D. and Hammond, G. S. *J. Am. Chem. Soc.* **76** (1954) 4124.
- Connick, R. E. and Hurley, C. R. *J. Am. Chem. Soc.* **74** (1952) 5012.
- Walsh, T. J. and Hausman, E. A. *Treatise Anal. Chem.* **8** (Part 2) (1963) 379.

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