

'Oxenoid' oxygen insertion vs. a radical mechanism in the oxidation of alkanes and alcohols: the case of aromatic peracids

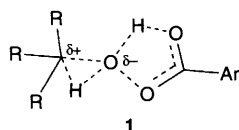
Anna Bravo, Francesca Fontana, Francesco Minisci* and Anna Serri

Dipartimento di chimica del Politecnico, via Mancinelli 7, I-20131 Milano, Italy

Adamantane is oxidised by MCPBA in a free-radical process, whose selectivity is discussed; by this method, cyclohexanol can be directly oxidised to caprolactone.

Aromatic peracids represent a class of oxidants, characterized by high selectivity in the oxidation of nonactivated C=H bonds, for which both an 'oxenoid' insertion¹ (1) and a free-radical mechanism² involving aroyloxy and aryl radicals as hydrogen abstracting species have been proposed. The suggested radical mechanism, however, is not consistent with the selectivity of the alkane oxidation. We therefore propose a different free-radical mechanism, based on our previous studies³ concerning the reaction of alkoxy radicals with hydroperoxides [reaction (1)].

Reaction (1) is very fast and is strongly affected by the ability of the solvent to form hydrogen bonds with hydroperoxides.^{3,4} Thus it seems reasonable to hypothesize also for reaction (2), by analogy with reaction (1), a high rate constant and an important solvent effect. Acylperoxy radicals are well-known hydrogen abstracting species in the autoxidation of aldehydes [reactions (3) and (4)]. The oxidation of alkanes would occur according to reaction (5). Reaction (5a) prevails over reaction (5b) and reactions (2) and (5a) are the propagating steps of the free-radical chain leading to the main reaction chain product ROH. The competitive decarboxylation of aroyloxy radicals⁵ would lead



to the classical reactions of aryl radicals. The high regioselectivity is mainly explained by the electrophilic character of the acylperoxy radical and the stereoselectivity observed with some alkanes^{1,2} should be ascribed to a fast cage reaction of the alkyl radical with the peracid reaction (5), an oxygen rebound mechanism]. A great deal of evidence and new synthetic developments support the oxidation mechanism of adamantane, cyclohexane, cyclohexanol, cyclopentanol, heptan-1-ol and heptan-2-ol by MCPBA [reaction (5)]. The evidence is as follows: (i) adamantane reacts at room temperature in 1,2-dichloroethane under argon to give 1-hydroxyadamantane 2,

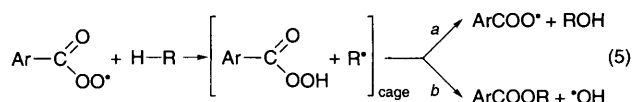
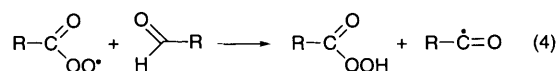
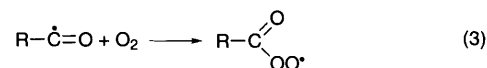
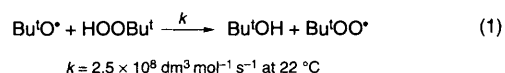


Table 1 Oxidation of adamantane by MCPBA^a

Solvent	Conv. (%)	T/°C	Yield (%)				Mono- and di-haloadamantanes
			2 ^b	3 ^b	4 ^b	5 ^b	
CH ₂ Cl-CH ₂ Cl ^c	30.2	18	70.1	1.6	19.3	18.1	not obs.
CH ₂ Cl-CH ₂ Cl ^d	29.4	18	77.2	1.3	11.4	not obs.	not obs.
CH ₂ Cl-CH ₂ Cl ^e	44.1	65	56.0	2.0	10.5	24.9	not obs.
CH ₂ Cl-CH ₂ Cl ^e	73.3	65	25.1	0.8	4.8	not obs.	63.0
CBrCl ₃ (0.25 mmol)							
CH ₂ Cl-CH ₂ Cl ^e	74.9	65	7.3	traces	traces	not obs.	77.2
CBrCl ₃ (0.5 mmol)							
CH ₂ Cl-CH ₂ Cl ^e	95	65	not obs.	not obs.	not obs.	not obs.	85.1
CBrCl ₃ (1 mmol)							
Benzene ^c	9.4	18	75.2	traces	18.3	not obs.	not obs.
Benzene ^d	11.4	18	74.5	0.9	17.7	not obs.	not obs.
Benzene ^e	21.0	65	84.6	4.5	10.8	not obs.	not obs.
CH ₂ Cl ₂ ^e	15.3	40	58.5	1.9	10.4	21.3	not obs.
CHCl ₃ ^e	49.9	60	29.4	1.2	2.5	9.5	18.1 (1-Cl)
CCl ₄ ^e	>99	65	ca. 1	not obs.	not obs.	not obs.	88.2

^a 1 mmol of MCPBA, 1 mmol of adamantane in 5 ml of solvent for 100 h at 18 °C and 20 h for all the other temperature. ^b Conversion of adamantane; all yields based on converted adamantane, except for yields of 5, based on MCPBA; ^c Argon atmosphere. ^d Oxygen atmosphere. ^e Air atmosphere. In benzene solution *m*-chlorobiphenyl is formed in (c), 5% and (e), 18%, but not in (d). Two experiments have been carried out in CHCl₃ and in CCl₄ in the absence of MCPBA according to procedure (e) and no chlorination took place. An experiment carried out according to procedure (c) in the absence of MCPBA, but in the presence of 1-adamantanol and MCPBA did not give 4.

2-hydroxyadamantane **3**, 1-adamantyl-*m*-chlorobenzoate **4** and chlorobenzene **5** (Table 1). In benzene solution **2**, **3**, **4** and *m*-chlorobiphenyl **6** are formed. Compounds **5** and **6** clearly arise from the chlorophenyl radical by hydrogen abstraction from the solvent and by homolytic substitution of benzene, respectively. (ii) In the absence of adamantane under the same conditions as (i), **5** and **6** are not formed. This means that adamantane induces the homolysis of MCPBA. (iii) Under the same conditions as in (i) but with an oxygen atmosphere, **2**, **3** and **4** are formed with similar selectivity, while **5** and **6** are absent. O₂ intercepts all the carbon-centred radicals escaping from the solvent cage, but not the adamantyl radical, which reacts rapidly with MCPBA in the cage. (iv) No reaction takes place in the absence of MCPBA under the conditions reported in (iii). (v) In CHCl₃, 1-chloroadamantane **7** is formed in addition to **2**–**5**. It is, however, well-known⁶ that tertiary alkyl radicals abstract both hydrogen and chlorine atoms from CHCl₃ at similar rates. (vi) In CCl₄ or in the presence of CBrCl₃ adamantane halogenation largely prevails over its oxidation (Table 1). (vii) No halogenation takes place under conditions (v) and (vi) in the absence of MCPBA. (viii) In the presence of TEMPO the oxidation is inhibited. (ix) The oxidation is inhibited in Bu^tOH, supporting, for reaction (2), a solvent effect similar to the one observed^{3,4} for reaction (1). (x) In dichloroethane solution cyclohexane is much less reactive than adamantane. In a competitive experiment at 20 °C C–H in adamantane is 100 times more reactive than C–H in cyclohex-

ane. At 60 °C the reaction products are cyclohexanol, cyclohexanone and caprolactone in the ratio 1:2:2 at low (10%) conversion of cyclohexane (cyclohexane–MCPBA = 5:1). Bromination of cyclohexane largely prevails in the presence of CBrCl₃. (xi) The oxidation of adamantane has been carried out under the conditions in which aldehyde autoxidation (butanal, benzaldehyde and *m*-chlorobenzaldehyde) takes place reactions (3) and (4)] (Table 2): **2**, **3** and esters with the same structure as **4** have been obtained with the same high selectivity observed with MCPBA. Since aliphatic peracids are unsuitable for alkane hydroxylation,² due to the very fast decarboxylation of the RCOO· radical (10¹⁰ s⁻¹ as compared with 10⁶ s⁻¹ for PhCOO·), the results with butanal strongly support the mechanism of reaction (5). The acylperoxy radical, formed according to reaction (3), thus provides a new, more useful procedure for selective alkane oxidation. (xii) In the presence of cyclohexanone, adamantane is not oxidized by MCPBA, caprolactone being the only reaction product (Baeyer–Villiger reaction). However, adamantane is selectively oxidized during the autoxidation of *m*-chlorobenzaldehyde in the presence of cyclohexanone, clearly indicating that the species responsible for the oxidation is not the peracid formed *in situ*, but the acylperoxy radical generated according to reaction (3). No oxidation takes place in any of the examples listed in Table 2 in the absence of aldehyde. (xiii) The prevailing formation of cyclohexanone and caprolactone in the oxidation of cyclohexane at low conversions is in striking contrast with previous reports⁷ stating that primary and secondary alcohols are unreactive with peracids in the absence of catalysis. Actually, cyclohexanol, cyclopentanol, heptan-1-ol and heptan-2-ol give the corresponding carbonyl compounds and the products of further oxidation (lactones, esters and carboxylic acids) simply by warming for a few hours at 60 °C with MCPBA in dichloroethane or keeping the mixture at room temperature for longer periods. (Table 3). Chlorobenzene is also a by-product in this case, and Bu^tOH, when used as solvent, inhibits the reaction. The previously reported⁷ inertness of alcohols towards MCPBA should therefore be ascribed to solvent effects, which inhibit reaction (2) by forming hydrogen bonds with peracids.

Table 2 Oxidation of adamantane and aldehydes by oxygen

Aldehyde	Conv. (%) ^a	T/°C	Yield (%)		1-Adamantyl ester (%) ^b
			2 ^b	3 ^b	
C ₃ H ₇ CHO ^c	47	70	78	traces	13
C ₆ H ₅ CHO ^c	31	70	84	traces	12.2
C ₆ H ₅ CHO ^d	36	40	82	1.3	6.1
<i>m</i> -ClC ₆ H ₄ CHO ^d	34	40	75	2.1	8.2
<i>m</i> -ClC ₆ H ₄ CHO ^e	20	70	72	2.8	7.3

^a Adamantane conversion. ^b Yields based on converted adamantane. ^c 2 mmol of aldehyde in 5 ml of dichloroethane are dropped during 3 h to a solution of 1 mmol of adamantane in 5 ml of dichloroethane and oxygen is bubbled for 24 h. ^d As in (c) by using 0.1 mmol of (Bu^tOOCO)₂. ^e As in (c) in the presence of 3 mmol of cyclohexanone.

Table 3 Oxidation of alcohols by MCPBA^a

Alcohol	Conversion (%) ^b	Reaction products (%) ^c
Cyclohexanol	75	caprolactone (87)
Cyclohexanol ^d	85	caprolactone (89)
Cyclopentanol	79	valerolactone (92)
Heptan-1-ol	70	heptanoic acid (78) hexyl formate (6.8) heptanal (2.6)
Heptan-2-ol	79	hexyl acetate (42.9) 2-heptanone (45.1) methyl hexanoate (2.5)

^a 1 mmol of alcohol and 2 mmol of MCPBA in 5 ml of dichloroethane at 60 °C for 20 h. ^b Alcohol conversion. ^c Yields based on converted alcohol. ^d As in (a) at 20 °C for 70 h 10–15% of chlorobenzene, based on MCPBA, is formed in all cases.

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