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Alkane oxygenation catalysed by gold complexes

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Abstract—Gold(III) and gold(I) complexes, $NaAuCl_4$ and $ClAuPPh_3$, efficiently catalyse the oxidation of alkanes by H_2O_2 in acetonitrile solution at 75°C. Turnover numbers (TONs) attain 520 after 144 h. Alkyl hydroperoxides are the main products, whereas ketones (aldehydes) and alcohols are formed in smaller concentrations. It is suggested on the basis of the bond selectivity study that at least one of the pathways in Au-catalysed alkane hydroperoxidation does not involve the participation of free hydroxyl radicals. Possibly, the oxidation begins from the alkane hydrogen atom abstraction by a gold oxo species. The oxidation of cyclooctane by air at room temperature catalysed by $NaAuCl_4$ in the presence of Zn/CH_3COOH as a reducing agent and methylviologen as an electron-transfer agent gave cyclooctanol (TON = 10). © 2001 Published by Elsevier Science Ltd.

Transition metal complexes are known to catalyse hydrocarbon oxidation with molecular oxygen and various oxygen atom donors, for example, with hydrogen peroxide.[1,2] Although gold complexes can catalyse certain transformations of organic compounds,[3–5] only a few examples of gold-catalysed alkane oxidations have been described.[6–10]

It has been found recently[11–13] that living cells of *Micrococcus luteus* are capable of transforming colloidal gold. These cells contain a specific NADPH-oxidase which includes gold (so called Au-protein) in its active centre. The Au-protein exhibited the activity in respect to methane.[13] Indeed, it was demonstrated by GC that the methane amount decreases in the incubation medium containing the Au-protein in the presence of NADPH, air, $K_3Fe(CN)_6$ and HCl buffer. It would be interesting to check the possibility of gold complexes catalysing alkane oxidations in vitro.

Herein we wish to report that gold(III) and gold(I) complexes catalyse the oxidation of the alkanes with hydrogen peroxide under relatively mild conditions: in acetonitrile solution at 75°C. The oxidations of hydrocarbons were carried out in air in thermostated (75°C) Pyrex cylindrical vessels with vigorous stirring. The total volume of the reaction solution was 10 mL. In all experiments, a 35% aqueous solution of hydrogen peroxide (Fluka) was used. The gold catalyst, usually employed in concentration 1.0×10^{-4} M, was introduced into the reaction mixture in the form of a stock solution in acetonitrile. The samples of the reaction solutions were analysed by GC (DANI-86.10; fused silica capillary column) twice: before and after addition of an excess of solid triphenylphosphine. Triphenylphosphine reduces hydrogen peroxide to water and the alkyl hydroperoxide to the corresponding alcohol, which allowed the determination of the *real* concentrations of the alkyl hydroperoxide, formed from the alkane, as well as those of the alcohol and the ketone (or aldehyde). In some cases, it is possible to find peaks corresponding to alkyl hydroperoxides. These peaks disappear completely after the treatment of the solution with PPh_3, while peaks of the corresponding alcohols grow (see Ref. 17). This method was developed and used by us previously[1,2,14–18] for the analysis of reaction mixtures obtained from various alkane oxidations.

Cyclooctane is oxidised by H_2O_2 in acetonitrile solution containing catalytic quantities of $NaAuCl_4$ to give cyclooctyl hydroperoxide, cyclooctanone and cyclooctanol. The total turnover number being 520 after 144 h (Fig. 1a). If $AgClO_4$ is added to the reaction mixture the oxidation proceeds substantially more rapidly (Fig. 1b). However, in this case, as in the reaction shown in Fig. 1a, the kinetic curve for the cyclooctyl hydroperoxide accumulation has an S-like shape. It is important that the oxidation catalysed by the gold(I) derivative $ClAuPPh_3$ occurs without auto-acceleration. Thus, it can be concluded that the gold(I) derivative is a catalyt-

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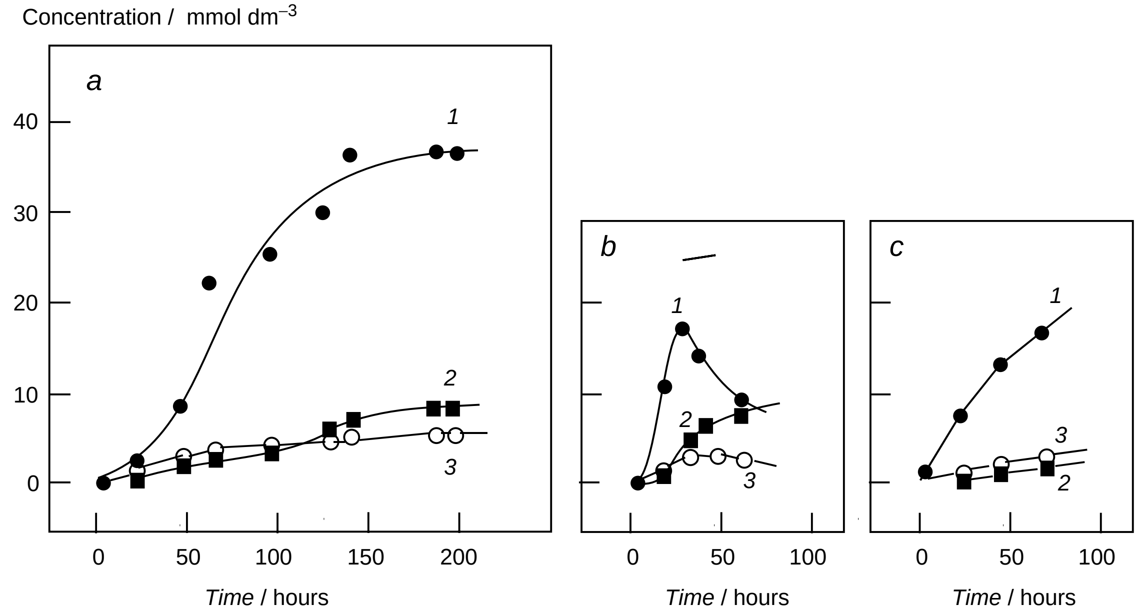

Figure 1. Accumulation of cyclooctyl hydroperoxide (curve 1), cyclooctanone (2) and cyclooctanol (3) in the oxidation of cyclooctane (0.16 M) with H_2O_2 (0.45 M) catalysed by $NaAuCl_4$ (1.0×10^{-4} M) (graph a), by $NaAuCl_4$ (1.0×10^{-4} M) in the presence of $AgClO_4$ (4.0×10^{-4} M) (graph b), and by $ClAuPPh_3$ (1.0×10^{-4} M) (graph c) at 75°C in acetonitrile solution.

ically active species which is generated after elimination of one or a few chloride anions (the silver derivative facilitates this elimination accelerating the oxidation process). In the oxidations catalysed by both gold(III) and gold(I) complexes, the alkyl hydroperoxide is the main product which gradually decomposes in the course of the reaction to produce relatively low amounts of the corresponding ketone and alcohol. Only in the presence of $AgClO_4$ the concentration of cyclooctanone is comparable with that of cyclooctyl hydroperoxide, and the curve for the accumulation of the latter has a maximum at approximately 30 h (Fig. 1b).

Cyclohexene (0.25 M) in the reaction catalysed by $NaAuCl_4$ under the same conditions gave after 48 h cyclohexene-3-ol as main product (0.050 M) as well as smaller amounts of 3-hydroperoxycyclohexene (0.003 M), cyclohexene-3-one (0.012 M) and the epoxide (0.0004 M). The total turnover number attained 654.

Oxidations of hydrocarbons by air or molecular oxygen in the presence of zinc powder as a reducing agent, carboxylic acid or its anhydride carried out in the presence[19–24] or in the absence[25,26] of alkylviologen as electron mediator are known to be models of some biological oxygenation systems.[1,2] We have found that the oxidation of cyclooctane by air at room temperature catalysed by $NaAuCl_4$ in the presence of Zn/CH_3COOH as a reducing agent and methylviologen as electron-transfer agent gave cyclooctanol (0.001 M) and a very small amount (0.0001 M) of cyclooctyl hydroperoxide (TON = 10). Cyclohexene under analogous conditions gave cyclohexene-3-ol (0.028 M), cyclohexene-3-one (0.011 M) and only 0.0008 M of the epoxide.

Selectivity parameters for the oxidation of certain hydrocarbons by both gold-containing systems are given in Table 1. The corresponding data are also summarised for the H_2O_2–VO_3^-–PCA reagent which is known to generate hydroxyl radicals,[14,17] and for the H_2O_2–$LMn^{IV}(O)_3Mn^{IV}L$–CH_3COOH [where L = 1,4,7-trimethyl-1,4,7-triazacyclononane] system,[18,27] which is believed to oxidise alkanes via attack of Mn(V)=O species on the C–H bond. It can be seen that in some cases (e.g. in the oxidation of *n*-heptane with H_2O_2–$ClAuPPh_3$ and O_2–$NaAuCl_4$–Zn–CH_3COOH–MV^{2+} systems, where MV^{2+} is the methylviologen cation) the selectivity practically equals the corresponding parameter for hydroxyl-generating V-reagent. However, usually in the oxidation of branched alkanes catalysed by the Au(I) and especially by the Au(III) complexes the bond selectivity is noticeably higher than that found for the V-reagent. Compare, for example, the values of the 1°:2°:3° parameter for the 2,4,4-trimethylpentane oxidation by H_2O_2–Au(III) (entry 1, 1:10:240), H_2O_2–Au(I) (entry 2, 1:18:120) and O_2–Au(III) (entry 3, 1:15:80) systems with the corresponding values for the H_2O_2–VO_3^-–PCA reagent (entry 4, 1:4:9) and for the H_2O_2–Mn(IV)–CH_3COOH system (entry 5, 1:5:55). It is interesting that this selectivity parameter is even higher in the case of the three Au systems than for the Mn system, which can be explained by great sterical hindrance in the attack of bulky Mn-containing species at highly branched isooctane. Sterical hindrance plays a much lesser role when isooctane is attacked with small hydroxyl radicals. The oxidation of less branched 3-methylhexane gave a higher value for the 1°:2°:3° parameter in the case of the Mn system.

Table 1. Selectivities of alkane oxidations by various systems in MeCN[a]

		Hydrocarbon oxidised (the selectivity parameter[b])						
		n-Heptane	3-MH	2,4,4-TMP	MCH	Adamantane	Toluene	
Entry	System	1:2:3:4	1°:2°:3°	1°:2°:3°	1°:2°:3°	2°:3°	M:R	*o*:*m*:*p*
1	H_2O_2–$NaAuCl_4$[c]	1:35:25:23	1:13:100	1:10:240	1:116:255	1.4	2.4	55:23:22
2	H_2O_2–$ClAuPPh_3$[c]	1:8:7.5:6.5	1:8:90	1:18:120	1:14:100			
3	O_2–$NaAuCl_4$[d]	1:5.7:6.1:5.1	1:5:60	1:15:80	1:11:90		0.35	55:23:22
4	H_2O_2–VO_3^-–PCA[e]	1:6.2:6.3:5.3	1:5.7:22	1:4:9	1:6:18	2.0	0.52	50:23:27
5	H_2O_2–Mn(IV)[f]	1:46:35:34	1:22:200	1:5:55	1:26:200		2.0	38:18:44
6	H_2O_2–$Fe(ClO_4)_3$[g]		1:4:30	1:5:45	1:7:43		1.1	60:26:14
7	H_2O_2–$Fe(ClO_4)_3$–PCA[g]		1:5:45	1:5:45	1:8:30		0.35	67:18:15

[a] The concentrations of alcohols formed in the reaction were measured after reduction with PPh_3. Substrates: 3-methylhexane, 3-MH; 2,4,4-trimethylpentane, 2,4,4-TMP (isooctane); methylcyclohexane, MCH.

[b] Parameter 1:2:3:4 is normalised (i.e. calculated taking into account the number of hydrogen atoms at each position) relative reactivities of hydrogen atoms in positions 1, 2, 3 and 4 of the hydrocarbon chain, respectively. Parameter 1°:2°:3° is normalised relative reactivities of hydrogen atoms at tertiary and secondary carbons, respectively. Parameter M:R is non-normalized relative reactivities of the methyl hydrogens and aromatic hydrogens. Parameter *o*:*m*:*p* is the non-normalized ratio of concentrations of *ortho*-, *meta*- and *para*-cresols formed in the reaction.

[c] At 75°C.

[d] In the presence of Zn/CH_3COOH as a reducing agent and MV^{2+} (MV^{2+} is methylviologen cation) as electron-transfer agent, at room temperature, in air.

[e] PCA, pyrazine-2-carboxylic acid. The oxidation at 30°C. For this system, see Refs. 1, 2, 14, 17 and 45.

[f] Complex $LMn^{IV}(O)_3Mn^{IV}L$, where L = 1,4,7-trimethyl-1,4,7-triazacyclononane. The oxidation at 20°C proceeds only in the presence of CH_3COOH in low concentration. For this system, see Refs. 2, 18 and 27.

[g] At room temperature.

Parameter t/c = [*trans*-decal-9-ol]/[*cis*-decal-9-ol], i.e. the ratio of concentrations of *trans*-decal-9-ol and *cis*-decal-9-ol formed in the oxidation of isomeric decalins, was approximately 4 in all cases testifying that the reaction proceeds non-stereoselectively.

Taking into account our preliminary data we can conclude that the Au-catalysed reactions does not seem to proceed only via $HO^\bullet$ radicals. Indeed, the bond selectivities in the oxidations of branched alkanes especially for the H_2O_2–$NaAuCl_4$ system are substantially higher (1°:2°:3° = 1:10–13:100–200) than that for the known from literature parameter for HO-radical-initiated oxidation (1°:2°:3° = 1:5.5:10).[28,29] The oxidation only via the Haber–Weiss mechanism,[28–32] is also doubtful because it is known that, for example, the radical t-$BuO^\bullet$ abstracts a hydrogen atom to give the 1°:2°:3° = 1:10:40 ratio.[28,29] Thus, it is reasonable to assume that in the Au-catalysed oxidations gold oxo or peroxo complexes are involved as oxidising species, together with $HO^\bullet$ (and possibly also $RO^\bullet$). The so-called[33,34] (see recent investigations in Gif chemistry[35–39]) Au^I–Au^{III} manifold could be possible:

$$Au^I + H_2O_2 \rightarrow Au^I{-}OOH + H^+ \rightarrow Au^{III}{=}O + H_2O$$

Then a high-valent gold oxo derivative attacks the C–H bond of an alkane, RH, leading to the formation of the alkyl hydroperoxide:

$$Au^{III}{=}O + RH \rightarrow Au^{II}{-}OH + R^\bullet$$

$$R^\bullet + O_2 \rightarrow ROO^\bullet$$

$$ROO^\bullet + Au^{II}{-}OH \rightarrow ROOH + Au^{III}{=}O$$

Of course, we realise that this scheme presents only one of the possible pathways for Au-catalysed alkane hydroperoxidation. The interaction between an alkane and a high-valent iron complex is believed to be the crucial step in hydrocarbon oxidations by some enzymes[1,2] (e.g. monooxygenases cytochrome P450[40–42] and methane–monoxygenase[43,44]). One could suspect that this principle is widely used in living nature and if so the Au-protein from *Micrococcus luteus* may oxidise methane via a similar mechanism. Evidently, much more detailed studies of alkane oxidations both in the living cells containing gold and in vitro catalysed by gold complexes are required in order to judge their mechanisms.

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