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Catalytic Oxidation of Alcohols into Aldehydes and Ketones by an Osmium-Copper Bifunctional System using Molecular Oxygen

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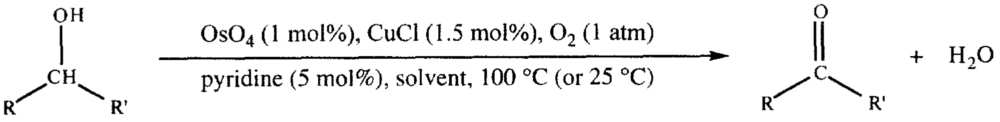
***Abstract*:** The oxidation of allylic and benzylic alcohols to aldehydes can be carried out at room temperature as low as 25°C with molecular oxygen, in the presence of the bifunctional osmium-copper system OsO_4-CuCl acting as the catalyst. © 1999 Published by Elsevier Science Ltd. All rights reserved.

Osmium tetroxide has been widely used in the dihydroxylation of olefins,[1] but so far has received little attention in the oxidation of alcohols.[2] Recently there has been great interest in catalytic oxidation processes, particularly in those that use molecular oxygen or air as the secondary oxidant.[3-12] This is of importance both environmentally and economically as water is formed as the only stoichiometric by-product and molecular oxygen or air is inexpensive and readily available. Heterobimetallic systems containing osmium offer great potential for such reactions (e.g. $[Os(N)R_2(CrO_4)]^-$, R = CH_3, CH_2SiMe_3).[13-14]

We have recently reported a ruthenium-copper bifunctional catalyst system that employs molecular oxygen as the secondary oxidant.[15] Using this method, we have been able to selectively oxidize primary benzylic and allylic alcohols to aldehydes. A similar system using only $(nPr_4N)(RuO_4)$ and molecular oxygen has also been reported, however, proved to be somewhat less selective.[16-17]

We report here our preliminary results on an OsO_4-CuCl bimetallic system that is an efficient catalytic system for the oxidation of alcohols with molecular oxygen producing water as the only by-product. The system we have developed involves the use of the bifunctional catalyst in the presence of pyridine and one atmosphere of molecular oxygen as the secondary oxidizing source, Figure 1.



R = alkyl, allyl, aryl
R' = H, alkyl, allyl, aryl

Figure 1

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The catalytic oxidation of various alcohols was carried out at 100 °C using OsO_4 (1 mol%), CuCl (1.5 mol%) and pyridine (5 mol%) in the presence of one atmosphere of molecular oxygen with toluene or 1,2-dichlorobenzene as the solvent. The results are presented in Table 1. As shown previously,[15][18] the addition of 4Å powdered molecular sieves results in slightly improved rates as degradation of the catalyst by water is prevented.

Table 1. Oxidation of alcohols to carbonyl compounds catalysed by an osmium-copper bifunctional system[a]

Entry	Substrate	t/h	Product	Yield[b] (%)	Selectivity (%)
1	4-$CH_3C_6H_4CH_2OH$	1	4-$CH_3C_6H_4CHO$	78	100
2	4-$CH_3C_6H_4CH(OH)CH_3$	1	4-$CH_3C_6H_4C(O)CH_3$	30	100
3	4-$CH_3OC_6H_4CH_2OH$	1	4-$CH_3OC_6H_4CHO$	96	100
4	2,4-$Cl_2C_6H_3CH_2OH$[c, d]	4	2,4-$Cl_2C_6H_3CHO$	62	100
5	2,6-$Cl_2C_6H_3CH_2OH$[c, d]	4	2,6-$Cl_2C_6H_3CHO$	35	100
6	4-$CH_3OC_6H_4CH_2OH$[c, e]	1	4-$CH_3OC_6H_4CHO$	46	100
7	*trans*-2-hexen-1-ol[c]	1	*trans*-2-hexenal	69	100
8	cinnamyl alcohol	2	cinnamyl aldehyde	19	100
9	3-buten-1-ol	2	no reaction	0	-
10	10-undecen-1-ol	1	10-undecenal	22	99
11	1-octanol[c, d]	2	octanal	32	92
12	5-nonanol[c]	1	5-nonanone	36	100
13	cyclobutanol[f]	5	cyclobutanone	84[g]	100

[a] General reaction conditions: 1 atm O_2, OsO_4 (1 mol%), CuCl (1.5 mol%), pyridine (5 mol%), 0.5g of 4Å powdered molecular sieves, in toluene (6ml) and at 100 °C. [b] GC determination. [c] In 1,2-dichlorobenzene (6 ml). [d] No pyridine added. [e] At 25 °C. [f] Conditions as in[a] with OsO_4 (4 mol%), CuCl (6 mol%). [g] Determined by ^{1}H-NMR spectroscopy.

The bifunctional OsO_4-CuCl catalyst was found to be relatively selective, with only benzylic, and to a lesser degree, allylic alcohols undergoing any significant oxidation (Table 1, entries 1 and 7). Secondary (Table 1, entry 12) and simple primary alcohols (Table 1, entry 11) were only sluggishly oxidized to the corresponding carbonyl product. Cyclobutanol appears to be a notable exception to the sluggish oxidation of secondary alcohols and is believed to be as a result of being less sterically encumbered. The oxidation reactions, therefore, appear to be sensitive to steric factors near the alcohol functional group. This is further supported by the increase in the rate of oxidation of 2,4-dichlorobenzyl alcohol (Table 1, entry 4) compared with 2,6-dichlorobenzyl alcohol (Table 1, entry 5). We have observed similar results in the $(nPr_4N)(RuO_4)$-CuCl/O_2 system.[15] This suggests that as with the $(nPr_4N)(RuO_4)$/NMO[18] and $(nPr_4N)(RuO_4)$-CuCl system the bifunctional OsO_4-CuCl reagent is sterically demanding, with oxidation presumably occurring through the intermediacy of osmate esters. The selectivity of the osmium-copper catalyst is similar to $(nPr_4N)(RuO_4)$-CuCl but is significantly different to that of the Griffith $(nPr_4N)(RuO_4)$/NMO system[18] and the $(nPr_4N)(RuO_4)/O_2$ system of Ley[16] and Markó,[17] where benzylic, allylic and aliphatic primary alcohols and secondary alcohols are all readily oxidized. As with the Griffith, Ley and Markó systems, functional groups such as double bonds remain intact during the oxidations. Although we have not tested the ultimate limits of turnover and scale of the reaction, turnover numbers greater than 330 have been obtained with benzylic alcohols. The rate of oxidation of various alcohols with the osmium-copper bifunctional system represents an improvement on the results obtained with the ruthenium-copper system,[15] although both systems were found to have similar selectivity.

In an attempt to improve the rate and selectivity of the catalytic oxidation process, the necessity of each component was investigated. It was found that increasing the concentration of CuCl from 1.5 mol% to 12 mol% had little effect on the catalytic activity (Table 2), whereas, changing the copper compound from CuCl to $CuCl_2$, $Cu(acac)_2$ or to Cu_2O resulted in a decrease in activity of the catalytic system. ***Importantly OsO_4 was found to catalytically oxidize benzylic alcohols with just dioxygen and no additives.*** However, the omission of CuCl led to a decrease in activity, although reasonable turnover numbers were observed. This is opposite to that found in the $(nPr_4N)(RuO_4)/O_2$ system where CuCl·phenanthroline was shown to retard the rate of oxidation.[17] The addition of pyridine (5 mol%) was detected to be necessary as without pyridine the reaction rates were much slower; this is similar to the ligand acceleration effect found in OsO_4 catalysed dihydroxylation reactions.[1] However, increasing the concentration of pyridine had very little effect on the rate of oxidation (Table 2). Interestingly the addition of pyridine to the catalytic mixture in the absence of CuCl resulted in a sharp decrease in the rate of oxidation. Changing the nitrogen donor ligand to 2-aminopyridine or the bidentate ligand bipyridine led to a slight decrease in activity. As expected lowering the temperature also had a negative effect on the rate of oxidation. However, benzylic alcohols could be oxidized at 25 °C with respectable rates with the OsO_4-CuCl-pyridine system in the presence of molecular oxygen with 1,2-dichlorobenzene as the solvent, with up to 180 turnovers observed (Table 1, entry 6). At ambient temperatures the use of 1,2,-dichlorobenzene is important, as using CH_2Cl_2 as the solvent resulted in a dramatic decrease in catalytic activity.

Table 2. Oxidation of $4\text{-}MeOC_6H_4CH_2OH$ to $4\text{-}MeOC_6H_4CHO$ using OsO_4 with different concentrations of pyridine and copper chloride.[a]

Entry	Pyridine (mol%)	CuCl (mol%)	t/h	Yield (%)[b]
1	0	0	1	31
2	0	1.5	1	49
3	0	12	1	51
4	3	0	1	18
5	5	1.5	1	78
6	50	1.5	1	79

[a] General reaction conditions: OsO_4 (1 mol%), 0.5g of 4Å powdered molecular sieves, in toluene (6ml), 1 atm O_2 and at 100 °C. [b] 100 % selectivity.

The mechanism of this bifunctional catalyst is uncertain. The observation that cyclobutanol is oxidized to cyclobutanone with total selectivity (Table 1, entry 13) would suggest that one-electron processes are not involved in the oxidation reaction.[19] It would also seem reasonable to suggest that the formation of osmate esters followed by C-H bond cleavage could be involved in the first step of the catalytic cycle.[20] However, the exact role of the copper compound in the catalytic reaction is unclear but a copper(II) species, generated from the reaction of copper(I) with molecular oxygen, may serve as an oxidant for the osmium tetroxide that is reduced in the reaction, although it is unlikely to take the osmium back to its initial oxidation state.

Finally we have found that as with the $(nPr_4N)(RuO_4)/O_2$ and $(nPr_4N)(RuO_4)\text{-}Cu/O_2$ systems, $OsO_4\text{-}Cu/O_2$ gives a very dark heterogeneous solution during catalysis. Preliminary experiments seem to indicate the formation of colloidal material in these reactions. Therefore, whether the catalysis occurs heterogeneously or homogeneously remains unknown. Studies on more stable bifunctional systems are underway to clarify this point.

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