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Journal of Organometallic Chemistry 649 (2002) 289–292

Journal of Organometallic Chemistry

www.elsevier.com/locate/jorganchem

Note

Oxidation of primary and secondary alcohols catalyzed by a pentamethylcyclopentadienyliridium complex

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Received 7 October 2001; received in revised form 14 November 2001; accepted 27 November 2001

Abstract

The oxidation of primary and secondary alcohols is carried out in acetone under mild conditions using catalytic amounts of $[Cp^{*}IrCl_2]_2$ and K_2CO_3. Primary alcohols are converted into the corresponding aldehydes with high selectivity in good yields. Secondary alcohols are readily oxidized to ketones with smaller amounts of the catalyst. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Iridium catalyst; Pentamethylcyclopentadienyl complex; Oxidation; Hydrogen transfer

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1. Introduction

The oxidation of alcohols to carbonyl compounds is one of the most fundamental and important reactions in synthetic organic chemistry, and it is usually achieved by use of stoichiometric amounts of harmful reagents, such as chromium reagents [1]. From an environmental viewpoint, it is quite important to develop a mild and less toxic oxidation reaction system. Recently, transition metal-catalyzed oxidation of alcohols, especially hydrogen transfer oxidation (Oppenauer-type oxidation) which can be achieved under mild and less toxic conditions with high selectivity as compared with many other oxidation methods, has been developed [2]. However, most of the reported hydrogen transfer oxidations have been mainly applicable to secondary alcohols, and relatively few examples of the oxidation of primary alcohols affording aldehydes as products have been known [2a,2b,2e,2i], although a variety of metal-catalyzed oxidative transformations of alcohols involving hydrogen transfer as a key step has been known [3]. During the course of our investigation on the chemistry of pentamethylcyclopentadienyl (Cp*) iridium complexes [4], we became interested in their catalytic activity which has been little explored [5], although their ability toward activation of small organic molecules by carbon–hydrogen bond cleavage has been revealed extensively in stoichiometric reactions [6]. We wish to report here a Cp*Ir complex-catalyzed oxidation of primary and secondary alcohols to give carbonyl compounds, which proceeds under mild conditions with use of acetone as an oxidant.

Table 1
Oxidation of benzyl alcohol to benzaldehyde by various catalytic system [a]

Entry	Catalyst	Acetone (ml)	Yield (%) [b,c]
1 [d]	$[Cp^{*}IrCl_2]_2$	10	13
2	$[Cp^{*}IrCl_2]_2$	10	71
3 [e]	$[Cp^{*}IrCl_2]_2$	10	69
4	$[Cp^{*}IrCl_2]_2$	30	87
5	None	10	0
6	$[IrCl(cod)]_2$	10	0
7	$[Cp^{*}RhCl_2]_2$	10	58
8	$RuCl_2(PPh_3)_3$	10	3

[a] The reaction was performed at room temperature for 6 h with benzyl alcohol (1.0 mmol), catalyst (2.0 mol%/metal) and K_2CO_3 (0.10 mmol) in acetone.

[b] Determined by GC based on benzyl alcohol.

[c] Conversion of benzyl alcohol was almost equal to the yield of benzaldehyde.

[d] Reaction was performed without K_2CO_3.

[e] Reaction was performed with 0.020 mmol of K_2CO_3.

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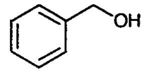
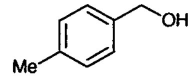
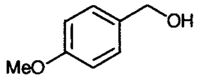
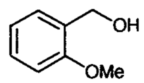
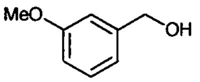
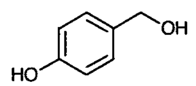
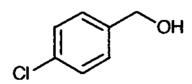
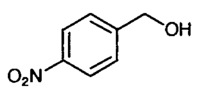
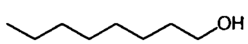
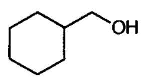
PII: S0022-328X(01)01461-9

Table 2
Oxidation of primary alcohols to aldehydes catalyzed by a pentamethylcyclopentadienyliridium complex[a]

Entry	alcohol	conv. of alcohol (%)[b]	yield of aldehyde (%)[b,c]
1		87	87 (74)
2		100	93 (82)
3		100	99 (90)
4		70	67 (63)
5		85	85 (77)
6[d]		77[e]	60[e]
7		72	70 (61)
8		32	20
9[f]		59	57 (44)
10[f]		51	47

[a] The reaction was performed at room temperature for 6 h with primary alcohol (1.0 mmol), $[Cp^*IrCl_2]_2$ (2.0 mol%/Ir) and K_2CO_3 (0.10 mmol) in acetone (30 ml).

[b] Determined by GC based on the starting alcohol.

[c] The value in parentheses is isolated yield.

[d] Reaction was performed with 1.1 mmol of K_2CO_3.

[e] Determined by ^1H-NMR.

[f] Reaction was performed at reflux temperature.

2. Results and discussion

Oxidation of benzyl alcohol to benzaldehyde was investigated with a variety of catalytic systems (Table 1). The reactions were carried out with benzyl alcohol in acetone at room temperature. In each reaction, benzaldehyde was formed as a single product; no formation of benzoic acid or other products was observed. The pentamethylcyclopentadienyliridium complex, $[Cp^*IrCl_2]_2$ exhibited some catalytic activity, affording benzaldehyde in a yield of 13% (entry 1). Addition of K_2CO_3 (0.10 mmol) as a base improved the catalytic activity to give benzaldehyde in a yield of 71% (entry 2). The reaction satisfactorily proceeded with use of even 0.020 mmol of K_2CO_3 (entry 3). When the reaction was carried out in a larger amount of acetone (30 ml), the yield increased up to 87% (entry 4). It was apparent that the reaction did not proceed at all without the catalyst (entry 5). Another iridium catalyst, $[IrCl(cod)]_2$ [cod = 1,5-cyclooctadiene], and a rhodium catalyst, $[Cp^*RhCl_2]_2$ were examined, but they showed lower activity than that of $[Cp^*IrCl_2]_2$ (entries 6 and 7). The ruthenium catalyst $RuCl_2(PPh_3)_3$, which has been reported as an excellent catalyst for the oxidation of secondary alcohols to ketones by Bäckvall and co workers [2c,2d], showed little activity for the present reaction (entry 8).

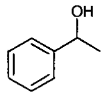
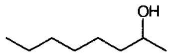
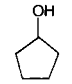
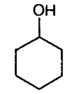
Results of oxidation of various primary alcohols by the present catalytic system are summarized in Table 2 The present oxidation reaction could be applied to substrates with various functional groups. In each reaction, no formation of carboxylic acid or condensation product of the aldehyde was observed. Benzyl alcohols with a substituent at the aromatic ring were transformed into the corresponding aldehydes (entries 2–8). The yield of aldehyde was much higher in the reaction of a substrate with an electron-donating group at the para-position (entries 2 and 3), while an electron-withdrawing group lowered the yield (entries 7 and 8). The yield was relatively low in the reaction of ortho-substituted substrate (entry 4), while the meta-substituent showed little effect (entry 5). *p*-Hydroxybenzyl alcohol could be also oxidized to give *p*-hydroxybenzaldehyde with use of excess amounts of a base (K_2CO_3) (entry 6). The present catalytic system was also applicable to oxidation of non-aromatic primary alcohols (entries 9 and 10), but these reactions should be carried out at reflux temperature to obtain moderate yields.

Results of oxidation of secondary alcohols by the present catalytic system are summarized in Table 3. In contrast to primary alcohols, secondary alcohols could be much easily oxidized to give the corresponding ketones with use of smaller amounts of the catalyst $[Cp^*IrCl_2]_2$ (0.50 mol%/Ir) and acetone (2 ml). 1-Phenylethanol, 2-octanol and cyclopentanol were transformed into the corresponding ketones in excellent yields (entries 1–3). Cyclohexanol was oxidized in rather lower yield (79%, entry 4) than the other secondary alcohols, showing a similar tendency to that observed in the ruthenium-catalyzed reaction [2c,2d].

When the oxidation of 1-phenylethanol was performed in acetone-d_6, formation of acetophenone containing no deuterium and $(CD_3)CHOH$ was observed by NMR analysis, indicating the apparent hydrogen transfer from 1-phenylethanol to acetone-d_6.

Although the mechanism for the present reaction, involving the catalytic active species being mononuclear or binuclear, is not completely clear as of yet, a possible mechanism is shown in Scheme 1. This is based on the ruthenium-catalyzed oxidation of secondary alcohols suggested by Bäckvall and co workers [2c,2d]. The first step of the reaction would involve the formation of metal alkoxide (**1**) followed by release of the product via β-hydride elimination accompanied with the formation of a metal hydride species (**2**). Formation of a iridium hydride species from the reaction of $[Cp^*IrCl_2]_2$ with alcohol and base is well-known process [5a]. The base (K_2CO_3) would stimulate the formation of metal alkoxide (**1**) by trapping hydrogen chloride generated at the first step of the reaction. Insertion of acetone into the metal–hydride bond in **2** to afford metal isopropoxide (**3**) and exchange of the alkoxy moiety would occur to regenerate metal alkoxide (**1**).

Table 3
Oxidation of secondary alcohols to ketones catalyzed by a pentamethylcyclopentadienyliridium complex [a]

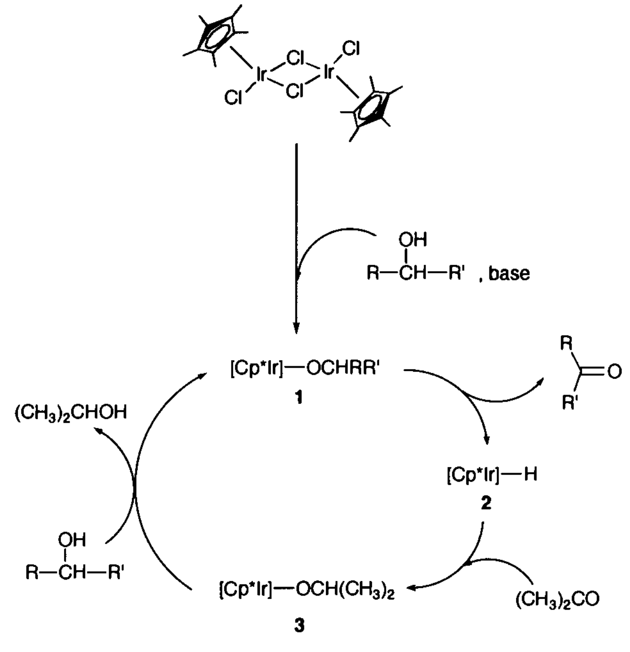
Entry	alcohol	conv. of alcohol (%)[b]	yield of ketone (%)[b,c]
1		100	100 (94)
2[d]		89	88 (77)
3		100	100
4[d]		79	79

[a] The reaction was performed at room temperature for 6 h with secondary alcohol (2.0 mmol), $[Cp^*IrCl_2]_2$ (0.5 mol%/Ir) and K_2CO_3 (0.20 mmol) in acetone (2.0 ml).

[b] Determined by GC based on the starting alcohol.

[c] The value in parentheses is isolated yield.

[d] Reaction was performed at reflux temperature.



Scheme 1.

In summary, we have shown a new catalytic system for hydrogen transfer oxidation applicable to primary and secondary alcohols under very mild conditions. It should be also noted that the present reaction is a rare example of utilization of pentamethylcyclopentadienyliridium complexes as catalyst. Further investigation on the application of this catalytic system to useful organic transformation is under way.

3. Experimental

3.1. General procedures

All reactions and manipulations were carried out under an atmosphere of Ar by means of standard Schlenk techniques. ^1H- and ^{13}C-NMR spectra were recorded on JEOL EX-270 and A-500 spectrometers. Column chromatography was carried out by using Wako-gel C-200. Gas chromatography (GC) analyses were performed on a Shimadzu GC-14A gas chromatograph with a capillary column (Shimadzu CBP1-M25-025). Acetone was dried with molecular sieves and distilled under Ar before use. The catalysts $[Cp^*IrCl_2]_2$ [5a,7], $[IrCl(cod)]_2$ [8], and $[Cp^*RhCl_2]_2$ [5a,7] were prepared by literature methods. Other reagents were used as obtained from commercial sources.

3.2. Procedure for iridium-catalyzed oxidation of primary alcohols

In a glass reactor under an atmosphere of Ar, $[Cp^*IrCl_2]_2$ (0.010 mmol) and K_2CO_3 (0.10 mmol) were suspended in C_3H_6O (30 ml) at room temperature (r.t.). Then the substrate (1.0 mmol) was added, and the mixture was stirred for 6 h. The yields were determined by GC analysis with decane or undecane as internal standard. Some of the products were isolated by silica gel column chromatography (eluent: hexane–ethyl acetate). The products were identified by comparison of their NMR data with those of authentic samples.

3.3. Procedure for iridium-catalyzed oxidation of secondary alcohols

In a glass reactor under an atmosphere of Ar, $[Cp^*IrCl_2]_2$ (0.0050 mmol) and K_2CO_3 (0.20 mmol) were suspended in C_3H_6O (2 ml) at r.t. Then the substrate (2.0 mmol) was added, and the mixture was stirred for 6 h. The yields were determined by GC analysis with undecane as internal standard. Some of the products were isolated by silica gel column chromatography (eluent: hexane–ethyl acetate). The products were identified by comparison of their NMR data with those of authentic samples.

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