Iridium-Catalyzed Carbonyl Allylations by Allylic Alcohols with Tin(II) Chloride

Yoshiro Masuyama,* Toshiya Chiyo, Yasuhiko Kurusu

Department of Chemistry, Faculty of Science and Technology, Sophia University, 7-1 Kioicho, Chiyoda-ku, Tokyo 102-8554, Japan
Fax +81(3)32383361; E-mail: y-masuya@sophia.ac.jp

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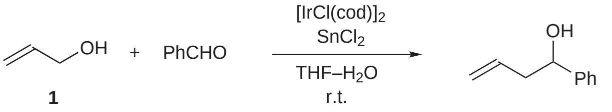
Abstract: Iridium complex $[IrCl(cod)]_2$ can function as a catalyst for the allylation of aldehydes and ketones by allylic alcohols upon addition of an equimolar amount of $SnCl_2$ in THF–H_2O; the reaction is carried out between room temperature and 50 °C to give the corresponding homoallylic alcohols.

Key words: nucleophilic addition, carbonyl allylation, π-allyliridium, tin(II) chloride, allylic alcohols

Complexes of group IX elements, such as $[RhCl(cod)]_2$, can catalyze the carbonyl allylation by allylic alcohols with $SnCl_2$ in THF–H_2O at 50 °C,[1] similarly to palladium-catalyzed carbonyl allylations.[2] A disadvantage of the palladium(0) cycle is that two equivalents of $SnCl_2$ are required for each equivalent of allylic alcohol.[3–5] In contrast, the reaction with rhodium(I) has been accomplished with one equivalent of $SnCl_2$. Here $SnCl_2$ acts as a reducing agent to accomplish the umpolung of the usual electrophilic π-allylrhodium(III) complex. It has been reported that π-allyliridium(III) complexes of other group IX elements can be prepared from iridium(I) complexes, such as $[IrCl(cod)]_2$ and allylic esters and can be used for reactions with nucleophiles.[6] Thus, we hoped that $[IrCl(cod)]_2$ would be active as a catalyst for carbonyl allylation by allylic alcohols with $SnCl_2$.

The catalytic activity of $[IrCl(cod)]_2$ with some ligands, along with varying the stoichiometry of $SnCl_2$, were investigated for the allylation of benzaldehyde with 2-propenol (**1**) in THF–H_2O at room temperature under a nitrogen atmosphere (Table 1). No allylation occurs without the addition of either the iridium catalyst or $SnCl_2$. The optimum reaction conditions employed equimolar amounts of **1** and $SnCl_2$ in THF (2 mL) and H_2O (0.1 mL) (Table 1, entry 7);[7] under these conditions the homoallylic alcohol was isolated after 20 hours in 87% yield. The allylation proceeded without H_2O, however, after a reaction time of 43 hours a low yield of homoallylic alcohol resulted (Table 1, entry 5). We also studied the effect of adding a ligand (entries 8–11); although the yields were lower, the character of the ligand did not have a significant effect. Under optimum conditions (Table 1, entry 7) $[IrCl(cod)]_2$ exhibited higher catalytic activity than either $IrCl(CO)(PPh_3)_2$ (89 h, 88%) or $IrCl_3$ (7 d, 0%). We also tested a number of tin(II) halides, however, lower yields resulted with SnF_2 (68 h, 12%) and $SnBr_2$ (67 h, 13%), while no reaction occurred even after 47 hours with SnI_2. As a solvent, THF was found to be superior to other solvents such as acetonitrile (44 h, 69%) and DMF (20 h, 79%).

Table 1 Allylation of Benzaldehyde with 2-Propenol (**1**)[a]



Entry	**1** (mmol)	$SnCl_2$ (mmol)	Ligand[b]	Time (h)	Yield (%)[c]
1	1.0	1.0	–	69	57
2	1.0	1.5	–	45	68
3	1.0	2.0	–	42	71
4	1.5	1.0	–	45	61
5	1.5	1.5	–	43	81 (13)[d]
6	1.5	2.0	–	44	84
7[e]	1.5	1.5	–	20	87
8[e]	1.5	1.5	PPh_3	20	58
9[e]	1.5	1.5	dppe	22	79
10[e]	1.5	1.5	dppb	22	76
11[e]	1.5	1.5	$P(C_6F_5)_3$	22	70

[a] The allylation of benzaldehyde (1.0 mmol) was carried out with $[IrCl(cod)]_2$ (0.02 mmol) in THF (3 mL) and H_2O (0.1 mL).
[b] Based on phosphorus (4 mol%).
[c] Isolated yields.[8]
[d] The figure in parentheses is the yield without H_2O.
[e] The reaction was carried out in THF (2 mL) and H_2O (0.1 mL).

Having optimized the reaction conditions, we subjected a range of aldehydes to the allylation (Table 2). Aromatic aldehydes bearing an electron-withdrawing or electron-donating group (Table 2, entries 1 and 2), an α,β-unsaturated aldehyde (Table 2, entry 3), and aliphatic aldehydes (Table 2, entries 4–7) were employed. This iridium catalytic system can also be utilized for the allylation of ketones with **1** (2.0 mmol) and $SnCl_2$ (2.0 mmol) at 50 °C, this is in contrast to the poor applicability of the rhodium catalytic system to ketones (Table 2, entries 8–11).[1]

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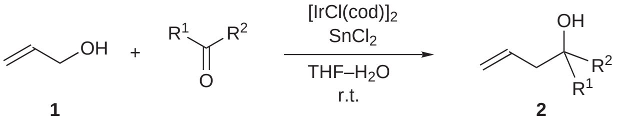
Table 2 Iridium-Catalyzed Carbonyl Allylation with **1**

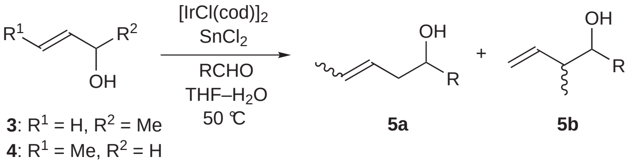


Entry	R^1	R^2	Time (h)	**2**; Yield (%)[a]
1	4-ClC_6H_4	H	17	91
2	4-$CH_3C_6H_4$	H	24	80
3	PhCH=CH	H	44	65
4	$PhCH_2CH_2$	H	48	67
5	$CH_2=CH(CH_2)_8$	H	47	53
6	C_6H_{13}	H	45	61
7	*c*-C_6H_{11}	H	45	55
8	Ph	CH_3	89	46
9[b]	C_6H_{13}	CH_3	49	48
10[b]	-$(CH_2)_4$-		44	41
11[b]	-$(CH_2)_5$-		46	59

[a] Isolated yields.[8]

[b] The reaction was carried out at 50 °C.

Table 3 Iridium-Catalyzed Carbonyl Allylation with **3** or **4**



Entry	R	**3** or **4**	Time (h)	Yield (%)[a]	**5a**/**5b** (**5b**; *syn/anti*)[b]
1	Ph	3	47	74	7:93 (41:59)
2	4-ClC_6H_4	3	45	78	5:95 (30:70)
3	4-$CH_3C_6H_4$	3	48	72	2:98 (40:60)
4	$PhCH_2CH_2$	3	48	59	2:98 (49:51)
5	C_6H_{13}	3	66	41	9:91 (40:60)
6	*c*-C_6H_{11}	3	74	49	67:33 (39:61)
7	Ph	4	49	70	8:92 (46:54)
8	4-ClC_6H_4	4	45	80	5:95 (43:57)
9	4-$CH_3C_6H_4$	4	49	72	8:92 (46:54)
10	$PhCH_2CH_2$	4	47	62	1:99 (45:55)
11	C_6H_{13}	4	68	46	8:92 (44:56)
12	*c*-C_6H_{11}	4	69	50	36:64 (37:63)

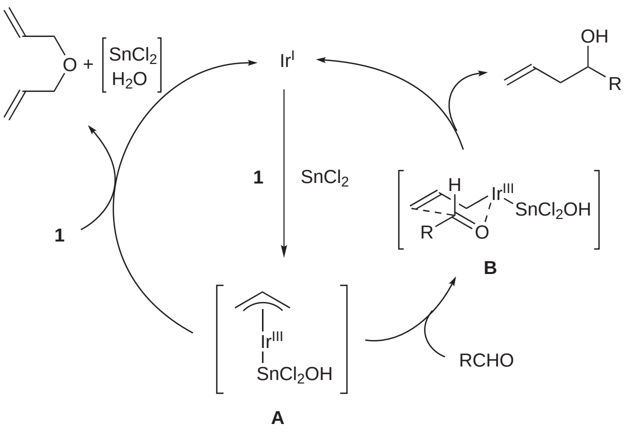
[a] Isolated yields.[8]

[b] The ratios were determined by ^1H NMR spectroscopy.

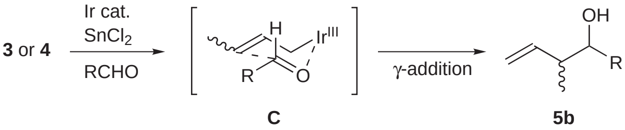
Regio- and diastereoselectivity were investigated for the iridium-catalyzed carbonyl allylation with 3-buten-2-ol (**3**) and 2-buten-1-ol (**4**). The allylation of benzaldehyde with **3** under optimum conditions for **1** was quite slow [**5** (R = Ph), 93 h, 62%; **5a**/**5b**, 1:99; **5b**-*syn*/**5b**-*anti*, 20:80]. In addition, the reaction of **4** at room temperature is not practical [**5** (R = Ph), 47 h, 8%, **5a**/**5b**, 15:85, **5b**-*syn*/**5b**-*anti*, 39:61]. The allylation of various aldehydes with **3** and **4** at 50 °C occurred at the allylic position substituted by a methyl group except for cyclohexanecarboxaldehyde,[9] while *anti*-diastereoselectivities were lower than that of benzaldehyde at room temperature (Table 3).

A study of the reaction of **1** (1.0 mmol) with $SnCl_2$ (1.2 mmol) in the presence of a catalytic amount of $[IrCl(cod)]_2$ (2 mol%) in THF-d_8 (0.75 mL) at room temperature without aldehyde or H_2O in a sealed tube by NMR spectroscopy (JEOL Λ-500) was undertaken. In contrast to both the preparation of the 2-propenyltin species in the palladium-catalyzed reaction[3] and the preparation of propene in the rhodium-catalyzed reaction,[1] diallyl ether was found to form.[10] A plausible mechanism for the iridium-catalyzed carbonyl allylation is illustrated in Scheme 1, based on both the γ-regioselectivity which was observed with both **3** and **4** and the NMR spectroscopic studies. The detection of diallyl ether suggests the formation of a π-allyliridium complex **A**; the π-allyliridium complex **A**, derived from **1** and $[IrCl(cod)]_2$ with $SnCl_2$, can undergo further nucleophilic attack by **1**.[6] The γ-regioselectivity using both **3** and **4** suggests the formation of a σ-allyliridium complex **B**; the preparation of **5b** from either **3** or **4** can be demonstrated by: (1) the transformation of an initial *syn*,*anti*-mixed 1-methyl-π-allyliridium complex derived from **3** or **4** into a mixture of (*E*)- and (*Z*)-2-butenyliridium complex **C** accompanied by the coordination of aldehydes; and then (2) the nucleophilic addition of the 2-butenyl moiety at the γ-position (Scheme 2).

In conclusion, $[IrCl(cod)]_2$ is superior to $[RhCl(cod)]_2$ as a catalyst for carbonyl allylation, because not only aldehydes but also ketones can be applied to the iridium-catalyzed allylation with **1**. The π-allyliridium complex **A**, derived from **1** with $SnCl_2$ and the iridium catalyst, should be an amphoteric allylating agent that can function either as an electrophile in the absence of an aldehyde or as a nucleophile in the presence of an aldehyde, unlike either palladium[3] or rhodium catalysts.[1]



Scheme 1



Scheme 2

References

(1) Masuyama, Y.; Kaneko, Y.; Kurusu, Y. *Tetrahedron Lett.* **2004**, *45*, 8969.

(2) For reviews containing carbonyl allylations by allylic alcohols via umpolung of π-allylpalladium, see: (a) Masuyama, Y. *J. Synth. Org. Chem., Jpn.* **1992**, *50*, 202. (b) Masuyama, Y. In *Advances in Metal-Organic Chemistry*, Vol. 3; Liebeskind, L. S., Ed.; JAI Press: Greenwich CT, **1994**, 255–303. (c) Tamaru, Y. In *Perspectives in Organopalladium Chemistry for the XXI Century*; Tsuji, J., Ed.; Elsevier Science: Switzerland, **1999**, 215–231. (d) Tamaru, Y. In *Handbook of Organopalladium Chemistry for Organic Synthesis*; Negishi, E., Ed.; Wiley: New York, **2002**, 1917–1953.

(3) For the palladium-catalyzed carbonyl allylation by allylic alcohols with $SnCl_2$, see: Takahara, J. P.; Masuyama, Y.; Kurusu, Y. *J. Am. Chem. Soc.* **1992**, *114*, 2577.

(4) Palladium-catalyzed carbonyl allylations need over two equivalents of reducing agent for one equivalent of allylic alcohol and/or aldehyde: (a) For triethylborane, see: Kimura, M.; Tomizawa, T.; Horino, Y.; Tanaka, S.; Tamaru, Y. *Tetrahedron Lett.* **2000**, *41*, 3627. (b) For indium iodide, see: Araki, S.; Kamei, T.; Hirashita, T.; Yamamura, H.; Kawai, M. *Org. Lett.* **2000**, *2*, 847. (c) For diethylzinc, see: Kimura, M.; Shimizu, M.; Tanaka, S.; Tamaru, Y. *Tetrahedron* **2005**, *61*, 3709.

(5) For nickel-catalyzed carbonyl allylation with over two equivalents of indium iodide and one equivalent of aldehyde, see: Hirashita, T.; Kambe, S.; Tsuji, H.; Omori, H.; Araki, S. *J. Org. Chem.* **2004**, *69*, 5054.

(6) Takeuchi, R. *Synlett* **2002**, 1954; and references cited therein.

(7) A typical procedure is as follows: To a solution of **1** (0.087 g, 1.5 mmol), benzaldehyde (0.11 g, 1.0 mmol), and $SnCl_2$ (0.28 g, 1.5 mmol) in THF (2 mL) and H_2O (0.1 mL) was added $[IrCl(cod)]_2$ (0.013 g, 0.02 mmol), and the solution was stirred at r.t. for 20 h. The solution was diluted with $Et_2O–CH_2Cl_2$ (2:1; 120 mL), washed with aq 10% HCl solution (20 mL), aq $NaHCO_3$ solution (20 mL), H_2O (20 mL), and brine (20 mL). The extracts were dried over anhyd $MgSO_4$. After evaporation of the solvent, column chromatography (silica gel; hexane–EtOAc, 7:1), and then HPLC (Japan Analytical Industry Co. Ltd., LC-908, JAIGEL-2H; $CHCl_3$) afforded 0.13 g (87%) of 1-phenyl-3-buten-1-ol as a colorless oil.

(8) The structures and/or ratios were confirmed by comparison of the IR and ^1H NMR spectra with those of authentic samples, see: (a) ref. 3 (b) Ito, A.; Kishida, M.; Kurusu, Y.; Masuyama, Y. *J. Org. Chem.* **2000**, *65*, 494.

(9) Since the reactivity of cyclohexanecarboxaldehyde is low, initially produced **5b** may react with excess cyclohexanecarboxaldehyde and isomerize to sterically unhindered and thermodynamically stable **5a** via a homoallyloxycarbenium ion intermediate: (a) Nokami, J.; Ohga, M.; Nakamoto, H.; Matsubara, T.; Hussain, I.; Kataoka, K. *J. Am. Chem. Soc.* **2001**, *123*, 9168. (b) Ref. 1.

(10) ^1H NMR (500 MHz): $\delta = 3.93$ (d, $J = 6$ Hz, 2 H), 5.09 (d, $J = 10$ Hz, 1 H), 5.23 (d, $J = 17$ Hz, 1 H), 5.83–5.91 (m, 1 H); ^{13}C NMR (125 MHz): $\delta = 71.5$, 116.0, 136.1.