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Iridium-catalyzed crossed aldol coupling and a new concept to form an Ir–Si species

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Abstract

$[Ir(COD)(PPh_3)_2]X$ ($X=PF_6$, ClO_4, and OTf) activated by H_2 molecule catalyzes Mukaiyama-type aldol coupling between enoxysilanes and acetals or aldehydes. An Ir–Si species formed in the first stage of the catalytic cycle plays an important role in these reactions.

Keywords: iridium catalyst; aldol coupling; enoxysilanes.

It is well known that iridium complexes possess efficient potential as catalysts for hydrogenation and isomerization of olefinic double bonds.[1] In particular, Ir(I) cationic complexes are utilized as an active catalyst for the synthesis of unsymmetrical allylsilanes[2] and enoxysilanes,[3] whereas examples reporting carbon–carbon bond formations catalyzed by Ir complexes are quite limited.[4] Thus, we focused our study to explore the characteristic aspects of Ir complexes. At the initial stage of our projects, we selected the Mukaiyama-type aldol coupling to evaluate the catalytic efficiency of $[Ir(COD)(PPh_3)_2]X$ (COD=1,5-cyclooctadiene) for the carbon–carbon bond formation. We report here that Ir(I) cationic complexes are active for the coupling reactions of enoxysilanes with aldehydes or acetals and that the formation of an Ir–Si species plays an important role in initiating the catalytic cycle for the carbon–carbon bond formation.

An aldol-type product **4aa** (13%) was isolated when a CH_2Cl_2 solution of benzaldehyde dimethylacetal (**2a**) with two equivalent moles of trimethylsilyloxypropene (**3a**) was heated for 1 h at 80°C in a sealed tube containing a catalyst solution prepared from $[Ir(COD)(PPh_3)_2]PF_6$ (**1a**) and H_2 molecule (Scheme 1). This catalyst system also showed moderate efficiency in the coupling of benzaldehyde (**5a**) with **3a** under similar conditions followed by protodesilylation to give **6aa** (41%). When similar types of the complex, $[Ir(COD)(PPh_3)_2]ClO_4$ (**1b**) and $[Ir(COD)(PPh_3)_2]OTf$ (**1c**, OTf=trifluoromethanesulfonyl), were used as a catalyst precursor for aldol couplings, the reaction rate and yield of the product were remarkably improved as shown in Table 1. In particular, the triflate complex **1c** worked quite efficiently

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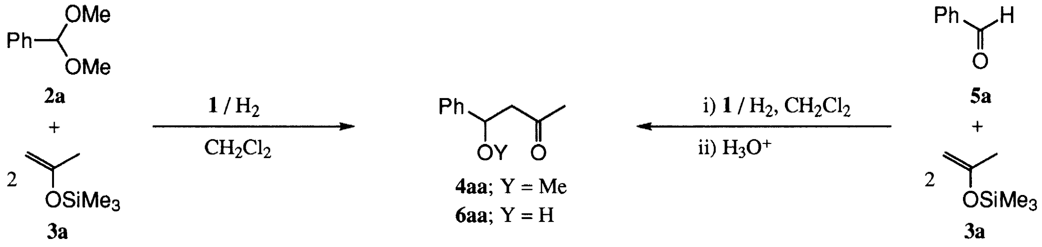
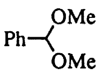
even at 25°C in the corresponding reaction within 3 h to give **4aa** and **6aa** in 93% and 86% yield, respectively (entries 4 and 8 in Table 1). Activation of the catalyst precursor with H_2 molecule is crucial for a sufficient yield of products. The yield of **4aa** lowered to 48% without this preliminary operation (entry 5 in Table 1).



Scheme 1.

Table 1
Ir-Catalyzed aldol-type coupling of **3a** with acetal **2a** or aldehyde **5a**[a]

Entry	Electrophile	$[Ir(COD)(PPh_3)_2]X$ (**1**) X	mol%	Conditions (°C/h)	Product	yield (%)
1	 (**2a**)	PF_6	1	80/1	**4aa**	13
2		ClO_4	3	25/19	**4aa**	67
3		ClO_4	1	80/1	**4aa**	86
4		OTf	3	25/3	**4aa**	93
5		OTf	3	25/3	**4aa**	48 [c]
6	Ph–CHO (**5a**)	PF_6	1	80/1	**6aa**	41
7	Ph–CHO (**5a**)	ClO_4	3	25/22	**6aa**	69
8	Ph–CHO (**5a**)	OTf	3	25/3	**6aa**	86

[a] Reactions were conducted on 1 mmole scale in a CH_2Cl_2 solution containing **1** activated by H_2 molecule.

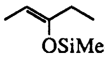
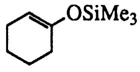
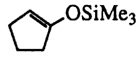
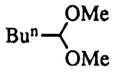
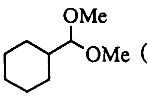
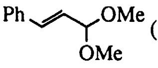
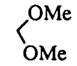
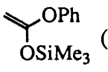
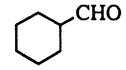
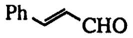
[b] Isolated yield as **4** or **6**.

[c] The precursor **1c** was not activated by the absorption of H_2 molecule.

Since **1c** was highly effective as a catalyst precursor for the aldol coupling of **3a** with **2a** or **5a**, some other types of starting materials were used to reveal the scope and limitations of **1c** in aldol couplings. The results are summarized in Table 2. Acetal **2a** reacted with enoxysilanes, **3c**, **3d**, and **3e** which need slightly severer conditions for sufficient yield of products than the reaction with **3a** because of the steric hindrance of the substituents on the nucleophilic site. Diastereoselectivity to form **4ac** seems to depend on the stereochemisitry of enoxysilane **3c**, though the extent of the selectivity is fair at present (entries 1 and 2 in Table 2). When cyclic enoxysilanes (**3d** and **3e**) were used as a nucleophile, appreciable *syn*-selectivity was observed (entries 3 and 4 in Table 2). Aliphatic acetals (**2b** and **2c**) and α,β-unsaturated acetal (**2d**) reacted readily with enoxysilanes, the substituents of which seem to retard the rate of coupling. This defect is surmounted by raising reaction temperature to 70°C. It should be noted that dimethoxymethane (**2e**) is also available as an electrophile in the present catalytic system (entry 12 in Table 2). In contrast to **5a** and **5d**, aliphatic aldehydes gave unacceptable results (entries 16 and 17 in Table 2).

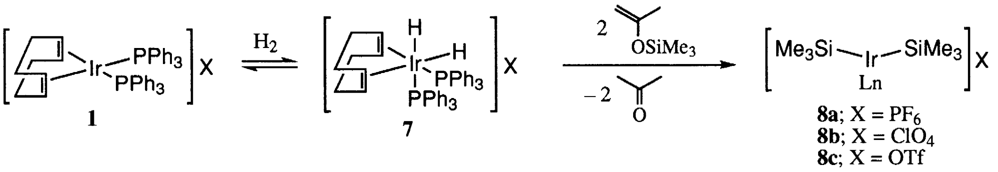
Cationic complexes **1b** and **1c** activated by H_2 molecule possess much higher catalytic ability for Mukaiyama-type aldol coupling than the Rh analogues,[5] though they are far less reactive than $TiCl_4$,[6] trityl perchlorate[7] and Me_3SiOTf.[8] Moreover, the anion part of **1** exerts remarkable catalytic efficiency,

Table 2
Aldol-type coupling catalyzed by $[Ir(COD)(PPh_3)_2]OTf$ (**1c**)[a]

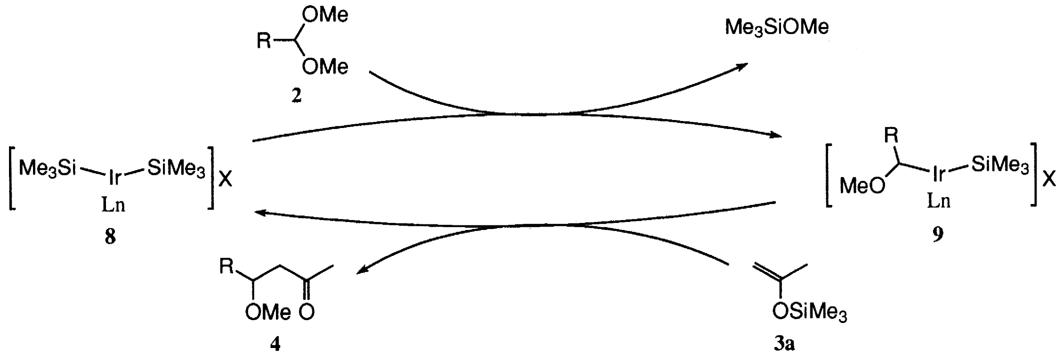
Entry	Electrophile	Enoxysilane	Mole% of catalyst	Conditions °C/h		Product yield (%) [b]	syn:anti [c]
1	**2a**	 *Z*-(**3c**)	1	70/3	**4ac**	96	43:57
2	**2a**	*E*-**3c**	1	70/3	**4ac**	98	68:32
3	**2a**	 (**3d**)	1	70/3	**4ad**	99	87:13
4	**2a**	 (**3e**)	1	70/3	**4ae**	99	87:13
5	 (**2b**)	**3a**	3	25/3	**4ba**	95	
6	 (**2c**)	**3a**	3	25/3	**4ca**	93	
7		*Z*-**3c**	1	70/3	**4cc**	75	59:41
8		*E*-**3c**	1	70/3	**4cc**	79	55:45
9		**3d**	1	70/3	**4cd**	59	[d]
10	 (**2d**)	**3a**	3	25/3	**4da**	95	
11		**3c** [e]	3	25/3	**4dc**	90	53:47
12	 (**2e**)	 (**3b**)	1		**4eb**	99	
13	Ph-CHO (**5a**)	*Z*-**3c**	1	70/3	**6ac**	99	45:55
14	Ph-CHO (**5a**)	*E*-**3c**	1	70/3	**6ac**	73	35:65
15	Ph-CHO (**5a**)	**3d**	1	70/3	**6ad**	9	56:44
16	Pentanal (**5b**)	**3a**	3	25/3	**6ba**	8	
17	 (**5c**)	**3a**	3	25/3	**6ca**	6	
18	 (**5d**)	**3a**	3	25/3	**6da**	72	

[a] The reactions were conducted on a 1 to 2 mmoles scale in a CH_2Cl_2 solution at 70 °C.
[b] Isolated yield. [c] The ratio was determined by GLC analyses using capillary columns (PEG 25 m or OV-1 25 m). [d] Diastereomers are not specified at present. [e] *Z*:*E* ≈ 70:30.

for example, $PF_6 < ClO_4 << OTf$. It is intuitively considered that **1** interacts with **3a** to form Me_3SiX which is a genuine catalyst for aldol coupling. This idea, however, can be ruled out by the fact that the signal ascribed to Me_3SiX is not detected at all in the ^1H NMR spectrum of a mixture containing an equivalent mole of **1** and **3a**, either in the presence or in the absence of H_2 molecule. A new species showing a Me_3Si signal (δ 0.16 ppm) and acetone appeared with the signal intensity corresponding to the quantity of the consumed **3a** in the ^1H NMR spectrum of a $CDCl_3$ solution of **1**, H_2 molecule, and **3a** at 25°C, regardless of the anionic part X. The identical species increases proportionally with **3a** added until the quantity reaches two equivalent moles. Although this new silyl species has not been isolated in pure form at present, the signal is elucidated by assuming the presence of an Ir–Si species **8** of which formation is described as shown in eq.1. Since it has been demonstrated that H_2 molecule adds oxidatively to **1a** to form **7** at −78°C,[9] the activation of **1** with H_2 molecule in our catalyst system would correspond to this step. Therefore the reaction of **7** with **3a** is regarded as a new method to form an Ir–Si bond. The formed **8** reacted rapidly with **2a** to form Me_3SiOMe. Thus, we can propose Scheme 2 as a plausible rationale for the present Ir-catalyzed aldol-type coupling. Further topics on the application of an Ir(I) complex catalyst are actively underway.



(1)



Scheme 2.

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