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Accounts

A Novel Catalysis of [{IrCl(cod)}$_2$] Complex in Organic Syntheses

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We have found that the [{IrCl(cod)}$_2$] complex catalyzes several reactions involving three-component couplings, hydrogen migration, vinyl ethers synthesis, and α-alkylation of ketones with alcohols, etc. Thus, the reaction of aldehydes, amines, and alkynes under the influence of a catalytic amount of [{IrCl(cod)}$_2$] complex led to three-component coupling products through a new type of C–H bond activation adjacent to the nitrogen atom of imines. Aziridines were also synthesized by three-component couplings of aldehydes, amines, and ethyl diazoacetate in the presence of a catalytic amount of [{IrCl(cod)}$_2$]. An innovation in the synthesis of vinyl ethers, which are very useful monomer materials in polymer syntheses but have been difficult to synthesize so far, was made by a simple exchange reaction of alcohols with vinyl acetates through a catalytic process using [{IrCl(cod)}$_2$]. A unique α-alkylation of ketones with alcohols was successfully achieved under the influence of [{IrCl(cod)}$_2$] and KOH without any solvents, leading to saturated ketones that elongated the carbon chain. Allyl homoallyl and diallyl ethers were converted by [{IrCl(cod)}$_2$] into γ,δ-unsaturated aldehydes via a Claisen rearrangement of in situ-generated allyl vinyl ethers. These reactions provide a novel synthetic tool for important chemicals like vinyl ethers and ketones, which are practically synthesized in the chemical industry.

Iridium complexes like [Ir(cod)(PCy$_3$)(py)]PF$_6$ were first used as effective catalysts for hydrogenation of olefins by Crabtree et al. in 1977.[1] Thereafter, Stork et al. reported the control of stereochemistry in catalytic hydrogenation of alkenes directing by the hydroxy function.[2] Pfaltz et al. disclosed the iridium complexes-catalyzed enantioselective hydrogenations of tri- and tetrasubstituted simple alkenes.[3] Thus, Ir complexes have become of interest as highly efficient hydrogenation catalysts, but until recent years they are not used as potent catalysts other than in the hydrogenation. In 1992, Murai et al. reported the iridium carbonyl complex-catalyzed reactions of hydrosilanes with alkenes or acetylene hydrazones under CO, leading to silyl enol ethers[4] or nitrogen-containing seven-membered heterocyles,[5] respectively. The dimerization of terminal alkynes affording *Z*-enynes was achieved by a cationic iridium complex.[6] Since iridium complexes were found to be effective as catalysts for carbon–carbon[7] and carbon–heteroatom bond formation,[8] many iridium-catalyzed coupling reactions have been developed.[9–11] The branched product selective allylic alkylation via a π-allyl iridium complex was established by Takeuchi et al.[7a] In 1998, Murahashi et al. reported that an iridium hydride complex, [IrH(CO)(PPh$_3$)$_3$], catalyzes an interesting dimerization of ethyl cyanoacetate via hydrogen transfer reaction.[12] The coupling of 1-naphthol with internal alkynes through the activation of the C–H bond of the 8-position of 1-naphthol is reported to be catalyzed by [{IrCl(cod)}$_2$].[13] On the other hand, iridium complexes bearing pentamethylcyclopentadienyl moiety are reported to catalyze efficiently several reactions such as the cleavage of aromatic 1,2-diols,[14b] the deuterium exchange reaction,[14c] and the hydrogen transfer reaction from alcohols to ketones.[14d–f]

In this account, we would like to describe our own recent works using [{IrCl(cod)}$_2$] complex: (i) carbon–carbon forming reactions, (ii) a novel synthesis of vinyl ethers and related compounds, (iii) hydrogen transfer reactions involving α-alkylation of ketones with alcohols, and (iv) isomerization of olefinic double bonds.

1. Carbon–Carbon Bond Forming Reactions

1.1 Three-Component Coupling Reaction of Aldehydes, Amines, and Alkynes. We have found that a new type of activation of the C–H bond adjacent to the nitrogen atom of imines catalyzed by an iridium complex leads to three-component coupling products of aldehydes, amines, and alkynes.[15] So far, no reports have appeared on the C–C bond forming reaction by the activation of the C–H bonds neighboring the nitrogen atom of imines.[16] The reaction of butyraldehyde, butylamine, and 1-octyne in the presence of a catalytic amount of [{IrCl(cod)}$_2$] in THF at 60 °C gave *N*-butylidene(2-hexyl-1-propylallyl)amine in 72% yield (Eq. 1). Several coupling reactions by the combination of aldehydes, amines, and 1-alkynes were examined. No reaction took place when *tert*-butylamine and internal alkynes were employed. It is interesting to note that the iridium-catalyzed reaction was not affected by water generated during the imine formation from amine and aldehyde. In fact, almost the same results were obtained when the

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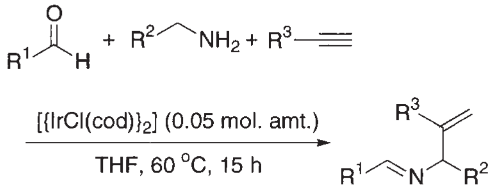
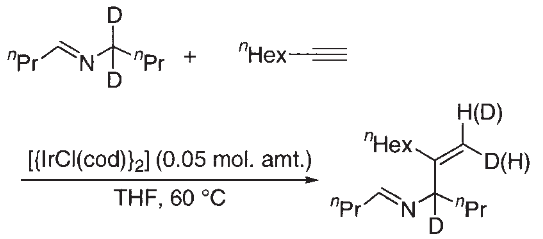
reaction was carried out by adding a small amount of water.



(1)

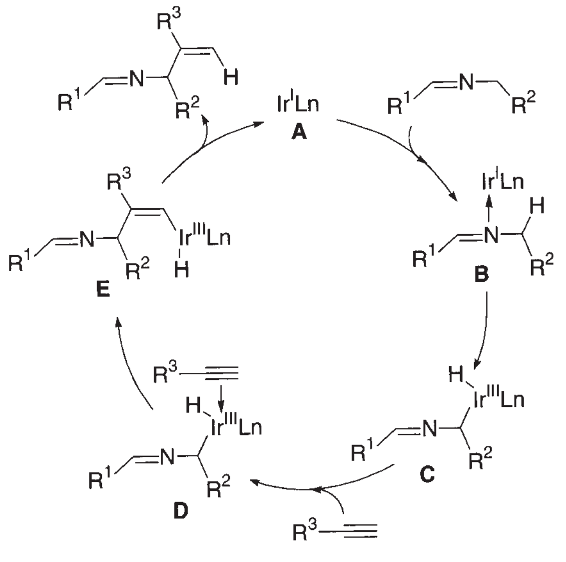
R^1, R^2, R^3 = ^{n}Pr, ^{n}Pr, ^{n}Hex	Yield 72%
^{n}Pr, ^{n}Pr, ^{n}Bu	Yield 74%
^{i}Pr, ^{n}Pr, ^{n}Hex	Yield 73%
^{t}Bu, ^{n}Pr, ^{n}Hex	Yield 62%
^{n}Pr, ^{i}Pr, ^{n}Hex	Yield 60%

In order to obtain further insight into the reaction pathway, we examined the reaction of *N*-butylidene-1,1-dideuteriobutylamine, prepared independently, under the influence of [{IrCl(cod)}$_2$] (Eq. 2). As expected, a coupling product in which a deuterium is incorporated to the terminal triple bond of the imine was produced. It is noteworthy that the coupling product consisted of a single geometrical isomer. These results suggest that the present reaction proceeds through the following reaction path (Scheme 1). At first, an Ir^{I} complex **A** coordinates to imine generated in situ from aldehyde and amine. The oxidative addition of the C–H bond adjacent to the nitrogen atom in the imine to the Ir^{I} complex would afford an Ir^{III} complex **C**. The coordination of alkyne followed by insertion to the complex **C** may give an iridium complex **E**, on which subsequent reductive elimination forms the coupling product.

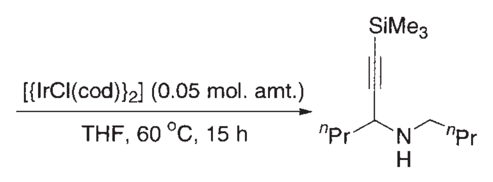


(2)

Interestingly, when trimethylsilylacetylene in place of 1-octyne was used in the iridium-catalyzed three-component coupling of aldehydes, amines, and alkynes, the unexpected product, where the alkyne was added to the double bond of imine, was obtained (Eq. 3). It is probable that the reaction proceeds through the oxidative addition of the terminal C–H bond of alkyne to the Ir^{I} complex, followed by the insertion of imine to the resulting Ir–H complex. Recently, Miyaura et al. have reported that the iridium-catalyzed dimerization of terminal alkynes involves the oxidative addition of alkyne to a low-valent Ir complex, followed by insertion of an alternative alkyne to give dimers.[17] After our finding, Carreira et al. reported the addition of TMS-acetylene to various aldimines, prepared independently from aldehydes and amines, catalyzed by [{IrCl(cod)}$_2$] leading to the corresponding adducts.[18]



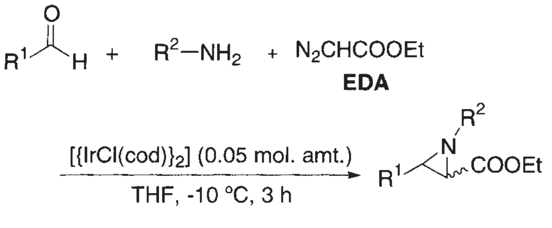
Scheme 1.



(3)

Yield 78%

1.2 Three-Component Coupling Reaction of Amines, Aldehydes, and Ethyl Diazoacetate. Aziridines are versatile compounds as precursors for the synthesis of various types of nitrogen-containing compounds that are biologically important, such as amino acids, amino alcohols, and lactams.[19] Although aziridines involving an aromatic moiety can be prepared by Lewis acid-catalyzed reactions using ethyl diazoacetate (EDA), there has been little study about the aziridine synthesis from aliphatic imines and EDA.[20] We have found that [{IrCl(cod)}$_2$] catalyzes the three-component coupling reaction of aliphatic aldehydes, aliphatic amines, and EDA to the corresponding aziridine derivatives under mild conditions.[21] Some representative results for aziridine synthesis are shown in Eq. 4. Although the La(OTf)$_3$-catalyzed three-component coupling reaction requires the presence of 5A molecular sieves,[22] the present reaction was performed without any dehydrating agents.



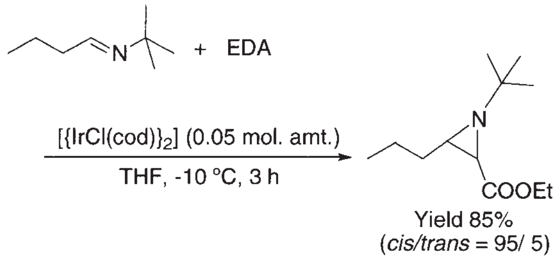
(4)

R^1, R^2 = ^{n}Pr, ^{n}Bu	Yield 71%
^{n}Pr, ^{n}Bu	No reaction$^{a)}$
^{n}Pr, ^{n}Bu	Yield 74%$^{b)}$
^{n}Pr, ^{n}Bu	Yield 79%$^{c)}$
^{n}Pr, ^{i}Bu	Yield 76%
^{n}Pr, ^{sec}Bu	Yield 83%
^{n}Pr, ^{t}Bu	Yield 83%
Ph, Ph	No reaction

a) $IrCl_3$ was used as a catalyst.
b) Hexane was used as a solvent.
c) EtOH was used as a solvent.

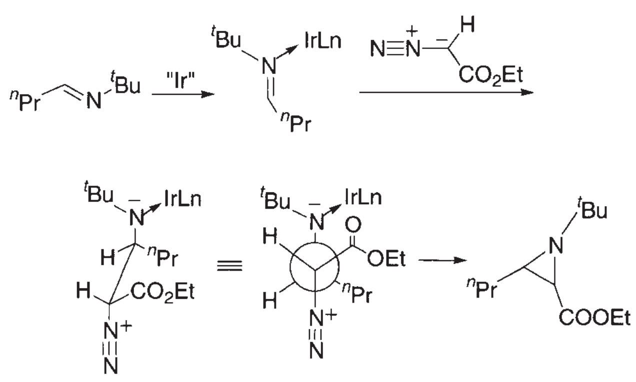
From a mechanistic point of view, it is of interest that the selectivity of aziridine is affected by the order of the addition of substrates to the catalytic solution. When an imine like *N*-(butylidene)butylamine was added to a THF solution containing [{IrCl(cod)}$_2$], the solution changed immediately from orange-red to light yellow, and EDA was added to this solution to form the corresponding aziridine. However, the addition of EDA to a THF solution of [{IrCl(cod)}$_2$] resulted in a change to dark purple, and the addition of imine produced aziridine and homo-coupling products of EDA, diethyl maleate and fumarate, whose formation may be explained by generation of carbene from EDA assisted by an Ir complex. These results suggest that the present Ir-catalyzed aziridination proceeds via the formation of an Ir–imine complex rather than an Ir–carbene complex.

For instance, the reaction of butanal, *tert*-butylamine, and EDA in the presence of a catalytic amount of [{IrCl(cod)}$_2$] at −10 °C afforded 1-*tert*-butyl-2-ethoxycarbonyl-3-propylaziridine in 83% in excellent stereoselectivity (*cis*:*trans* = 96:4) (Eq. 5). This high stereoselectivity of the aziridination can be explained by the following reaction path (Scheme 2). It is possible that the Ir complex coordinates to imine, followed by nucleophilic attack of EDA from the direction to reduce the steric repulsion between the ester moiety of the incoming EDA and *tert*-butyl group of the imine to form the corresponding *cis*-product.



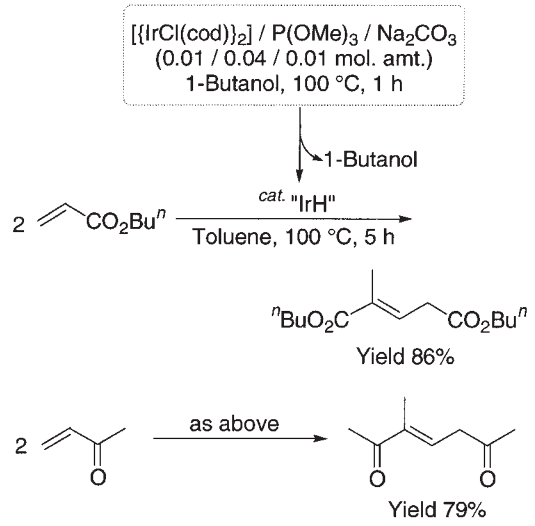
(5)

In contrast to the Ir-catalyzed three-component coupling reaction of amines, aldehydes, and alkynes, where the oxidative addition of the C–H bond adjacent to the nitrogen atom in the imine to Ir complex occurred, the reaction of amines, aldehydes, and EDA did not proceed through the C–H bond activation. Although the detail of the reaction mechanism of the coupling reaction of amines, aldehydes, and alkynes is not clear at this stage, the alkyne may coordinate to the Ir complex, and the resulting Ir complex could activate the C–H bond adjacent to the nitrogen atom in the imine.



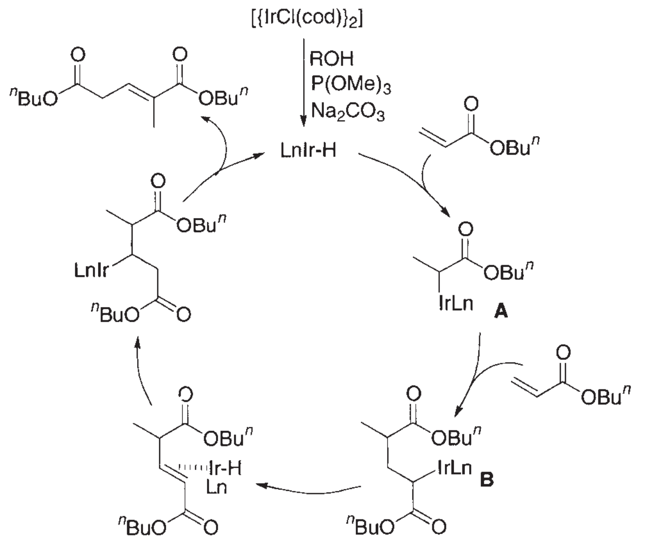
Scheme 2.

1.3 Head-to-Tail Dimerization of Acrylates. The dimerization of functional alkenes like acrylates and acryronitrile is an attractive route to obtain bifunctional compounds like dicarboxylates and diamine, respectively. The tail-to-tail dimerization of acrylates can be achieved by various transition metal compounds like Co,[23a,b] Ni,[23c] Ru,[23d–f] Rh,[23g–k] and Pd,[23l–n] but only a limited number of reports have appeared on the selective head-to-tail dimerization. We found that the head-to-tail dimerization of acrylates and vinyl ketones was catalyzed by an iridium hydride complex generated in situ from [{IrCl(cod)}$_2$] and alcohols in the presence of P(OMe)$_3$ and Na$_2$CO$_3$.[24] The reaction of butyl acrylate in the presence of [{IrCl(cod)}$_2$] in 1-butanol led to a head-to-tail dimer, 2-methyl-2-pentenedioic acid dibutyl ester, (53%) along with butyl propionate (35%) which is formed by the hydrogen transfer from 1-butanol. In order to avoid the formation of butyl propionate, the reaction was examined in several solvents like THF and toluene. However, no products were obtained by the reaction in such solvents. Thus, 1-butanol was removed from the catalytic solution after treatment of a mixture of [{IrCl(cod)}$_2$], P(OMe)$_3$, and Na$_2$CO$_3$ in 1-butanol at 100 °C for 1 h, and then butyl acrylate in toluene was added and reacted at 100 °C for 5 h to give a head-to-tail dimer in 86% (Eq. 6). Under these conditions, methyl vinyl ketone was also dimerized to form a head-to-tail dimer, 3-methy-3-heptene-2,6-dione (Eq. 6). It is interesting to note that the present reaction was promoted in methanol, ethanol, and 2-butanol, while no reaction occurred in *tert*-butyl alcohol having no α-hydrogen. These results suggest that an iridium hydride complex generated in situ from [{IrCl(cod)}$_2$] and alcohols in the presence of P(OMe)$_3$ and Na$_2$CO$_3$ promotes the head-to-tail dimerization of acrylates.



(6)

It is interesting to reveal the reaction course for the selective head-to-tail dimerization of acrylates by [{IrCl(cod)}$_2$]. Although we have unambiguous evidence for the high head-to-tail selectivity of the present dimerization, the following reaction path may be proposed (Scheme 3). An acrylate coordinates to an in situ-generated iridium hydride complex and then inserts into the Ir–H bond to form a σ-Ir complex **A** to which the coordination and insertion of another acrylate lead to an iridium complex **B**. The β-hydride elimination of an iridium hydride from the intermediate **B**, followed by the isomerization of the



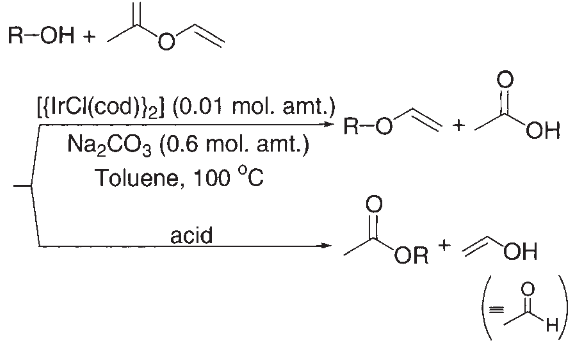
Scheme 3.

double bond to a more stable internal alkene results in a head-to-tail dimer.

2. A Novel Synthesis of Vinyl Ethers via an Unusual Exchange Reaction

Vinyl ethers are important raw materials as practical chemicals for the production of glutaraldehyde as well as vinyl polymer materials containing oxygen which are expected to degrade easily in nature. Practically, vinyl ethers are prepared by the reaction of acetylene with alcohols developed by Reppe et al. in 1956.[25] The reaction must be carried out under severe conditions at higher pressure (2–5 MPa) and temperature (180–200 °C) in the presence of KOH as a catalyst. Several other methods to prepare vinyl and alkenyl ethers are reported: e.g., mercury-catalyzed transvinylation of alcohols with vinyl ethers,[26] elimination of the alcohol moiety or HBr from acetals or α-bromo ethers, respectively,[27,28] isomerization of allyl ethers,[29] and carbometalation of alkynic ethers.[30] But, employment of these methods is limited to small-scale synthesis, and some methods call for the use of very toxic metals. Despite numerous attempts to overcome these drawbacks, no versatile methods have appeared for the synthesis of vinyl ethers so far.

We found that [{IrCl(cod)}$_2$] catalyzes efficiently a new type of exchange reaction between vinyl acetate and alcohols or phenols, leading to the corresponding vinyl ethers (Eq. 7).[31] Usually, the acid-catalyzed exchange reaction between alcohols and vinyl acetate results in alkyl acetates and vinyl alcohol which is readily isomerized to acetaldehyde.



(7)

Table 1. Vinylation of Octyl Alcohol with Vinyl Acetate under the Selected Conditions[a)]

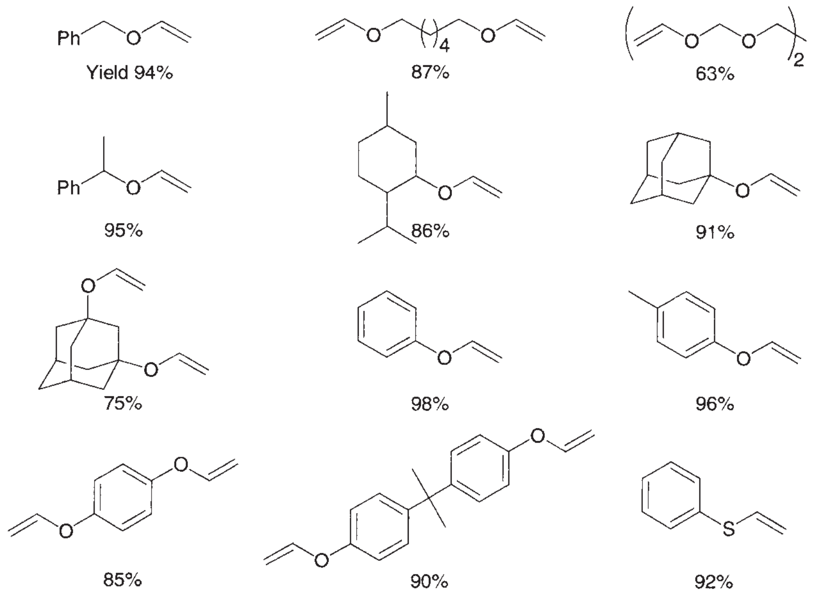
Run	Complex	Base	Conv./%	Yield/%
1	[{IrCl(cod)}$_2$]	Na_2CO_3	100	>99
2	[{IrCl(cod)}$_2$]	none	3	1
3	[{IrCl(cod)}$_2$]	NaOAc	100	82
4	[{IrCl(cod)}$_2$]	K_2CO_3	39	3
5	[{IrCl(cod)}$_2$]	Cs_2CO_3	30	6
6	[{IrCl(cod)}$_2$]	Pyridine	2	1
7	[Ir(cod)$_2$]BF$_4$	Na_2CO_3	72	70
8	[{RhCl(cod)}$_2$]	Na_2CO_3	28	3
9	[RuCl$_2$(cod)]	Na_2CO_3	4	4
10	[PtCl$_2$(cod)]	Na_2CO_3	9	1
11	Pd(OAc)$_2$/PPh$_3$	Na_2CO_3	0	0

a) Octyl alcohol (1 mmol) was allowed to react with vinyl acetate (2 mmol) in the presence of transition metal complex (0.01 mmol) and base (0.6 mmol) in toluene (1 mL) at 100 °C for 2 h under Ar.

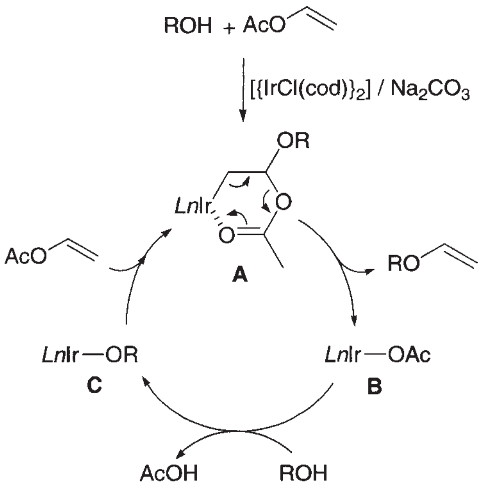
Table 1 summarizes the representative results for vinylation of octyl alcohol with vinyl acetate under various reaction conditions. When a mixture of [{IrCl(cod)}$_2$], vinyl acetate, alcohol, and Na_2CO_3 (the molar ratio is 0.01:2.0:1.0:0.6) in toluene was stirred at about 100 °C for 2 h, octyl vinyl ether was obtained in almost quantitative yield (Run 1). It is worth noting that the present reaction stopped at the stage of vinyl ether formation, since in the Pd-catalyzed reaction the vinyl ethers formed would tend to react further with an additional alcohol to form acetals rather than vinyl ethers. Almost no reaction took place in the absence of a base (Run 2). NaOAc was also efficient for the present reaction, but K_2CO_3, Cs_2CO_3, and pyridine were inert (Runs 3 to 6). Cationic iridium complexes possessed high catalytic activity for the present reaction, while other transition metal complexes such as Rh, Ru, and Pt complexes were inert (Runs 7–10). In the case of the reaction with the Rh complex, octyl acetate was obtained in low yield (Run 8). The reaction was not promoted at all by a Pd(OAc)$_2$/PPh$_3$ system under these conditions (Run 11).

A wide variety of vinyl ethers could thus be synthesized by this method (Scheme 4). Some of these products are not now available from commercial suppliers, although usage of these vinyl ethers is expected to be very interesting in polymer chemistry as components of homo- and copolymers. This catalytic vinylation system was found to be applicable to the synthesis of vinyl ethers from secondary and tertiary alcohols. Notably, thiophenol reacted with vinyl acetate to form vinylthiobenzene in 92% yield, since sulfur compounds frequently inhibit transition metal-catalyzed reactions.

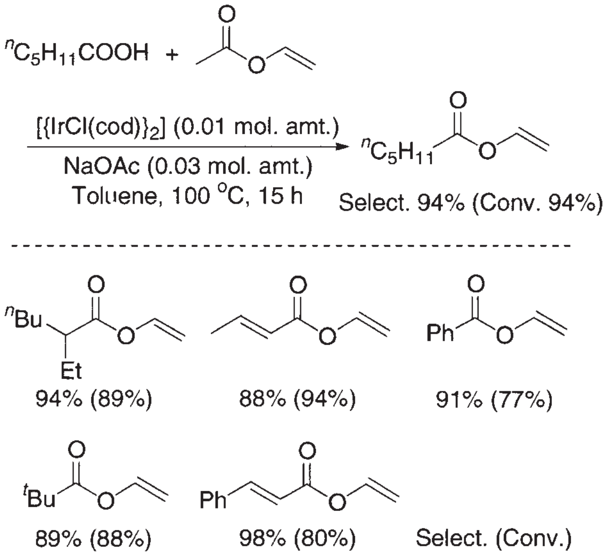
In order to obtain mechanistic information, we allowed phenol-*d* to react with vinyl acetate under these conditions. It was found that no deuterium was introduced into the resulting phenyl vinyl ether. This may suggest that the following reaction path through an intermediate **A** resulted from the reaction of [{IrCl(cod)}$_2$] with vinyl acetate and alcohol under the influence of Na_2CO_3 (Scheme 5). The release of an alkyl vinyl ether from the intermediate **A** gives rise to an iridium acetoxy complex **B**, which then reacts with alcohol, leading to an iridium alkoxy complex **C**; the coordination of the vinyl acetate to the complex **C** followed by insertion regenerates the **A**.



Scheme 4.



Scheme 5.



Scheme 6.

Recently, the palladium-catalyzed synthesis of allyl vinyl ethers by transfer vinylation between allyl alcohols and vinyl ether was reported by Schlaf and co-workers.[32] They showed that allyl alcohol was vinylated with 20 molar amounts of butyl vinyl ether under the influence of $[Pd(O_2CCF_3)_2(dpp)]$ (dpp = 4,7-diphenyl-1,10-phenanthroline).

On the other hand, the transfer vinylation between carboxylic acids and vinyl acetate is performed by some palladium and ruthenium compounds.[33] But, these reactions sometimes require a relatively higher reaction temperature (130–150 °C). We found that a variety of carboxylic acids were converted into the corresponding vinyl esters with excellent yields by allowing them to react with vinyl acetate in the presence of $[\{IrCl(cod)\}_2]$ and NaOAc at 100 °C (Scheme 6).[34] Recently, it was reported that the addition of carboxylic acids to alkynes was efficiently promoted by Ru.[35]

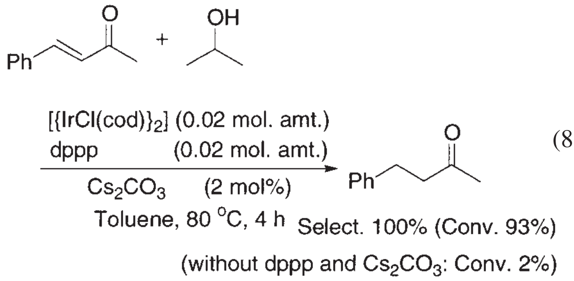
3. Hydrogen Transfer and Related Reactions

3.1 Selective Hydrogenation of α,β-Unsaturated Carbonyl Compounds with Alcohol.

Chemoselective reduction of α,β-unsaturated carbonyl compounds using an alcohol as a hydrogen source has been widely studied. The selective reduction of the carbonyl group of α,β-unsaturated compounds to allylic alcohols has been achieved with ease.[36,37] In contrast, the transfer hydrogenation of the alkenic double bond of conjugated enones is limited.[38] The transfer hydrogenation of conjugated enones with an alcohol is performed by the use of ruthenium[36a–c,39] or rhodium[40] complexes, but the reduction using iridium complexes is rare.[37]

We found that the $[\{IrCl(cod)\}_2]$/phosphine/base system serves as an efficient catalyst for the reduction of α,β-unsaturated carbonyl compounds and of carbonyl compounds using 2-propanol as a hydrogen source.[41] Treatment of 4-phenyl-3-buten-2-one with 2-propanol under the influence of catalytic amounts of $[\{IrCl(cod)\}_2]$, $Ph_2P(CH_2)_3PPh_2$ (dppp), and Cs_2CO_3 at 80 °C for 4 h gave 4-phenyl-2-butanone with

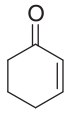
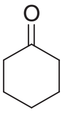
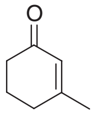
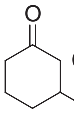
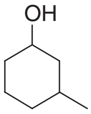
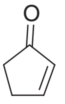
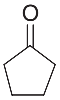
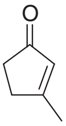
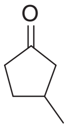
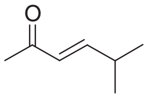
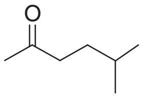
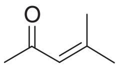
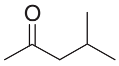
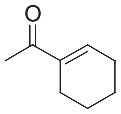
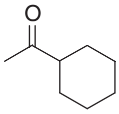
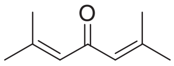
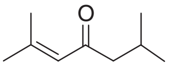
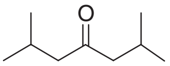
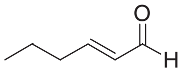
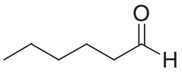
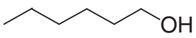
100% selectivity at 93% conversion (Eq. 8). Almost no reaction took place in the presence of [{IrCl(cod)}$_2$] complex alone.



(8)

Table 2 summarizes the results for the transfer hydrogenation of various α,β-unsaturated carbonyl compounds using the [{IrCl(cod)}$_2$]/dppp/Cs$_2$CO$_3$ system. A variety of α,β-unsaturated ketones were reduced to the corresponding ketones in excellent yields except for 3-methyl-2-cyclohexen-1-one which was reduced to the corresponding alcohol (Runs 1 to 8). 2-Hexenal under these reaction conditions afforded hexanal (70%) and hexanol (7%) at 75% conversion (Run 9).

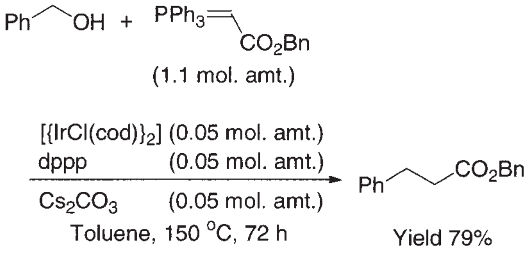
Table 2. Transfer Hydrogenation of Various α,β-Unsaturated Carbonyl Compounds Catalyzed by [{IrCl(cod)}$_2$]$^{a)}$

Run	Substrate	Conv. /%	Product	(Selectivity/%)
1		99		(98)
2$^{b)}$		91	 (70) 	(25)
3$^{b)}$		96		(94)
4$^{c,d)}$		79		(96)
5		99		(95)
6$^{d)}$		90		(98)
7$^{c,e)}$		78		(96)
8$^{c,e)}$		68		(74)
				(26)
9		75		(70)
				(7)

a) Substrate (0.5 mmol) was allowed to react with 2-propanol (5.0 mmol) in the presence of a catalytic amount of [{IrCl(cod)}$_2$] (0.01 mmol), dppp (0.01 mmol), and Cs$_2$CO$_3$ (0.01 mmol) in toluene (0.5 mL) at 80 °C for 4 h. b) [{IrCl(cod)}$_2$] (0.005 mmol), dppp (0.005 mmol), Cs$_2$CO$_3$ (0.005 mmol). c) Cs$_2$CO$_3$ (0.005 mmol). d) 15 h. e) 75 °C, 6 h.

Tani et al. reported that simple alkynes and alkenes were reduced with methanol under the influence of an iridium hydrido(methoxo) complex prepared by the reaction of [{Ir(bpbp)Cl}$_2$] (bpbp = 2,2′-bis(diphenylphosphino)-1,1′-biphenyl) with methanol.[42] They suggested that an iridium dihydride complex was formed and acted as the real catalyst. The coordination of the iridium complex to alkene, followed by hydride insertion, gave the corresponding alkane. The reaction pathway of the present transfer hydrogenation by [{IrCl(cod)}$_2$]/dppp/Cs$_2$CO$_3$ is not fully confirmed at this stage, but it seems likely that the reaction proceeds through a similar pathway, as reported by Tani et al. The reaction may be initiated by the coordination of an iridium hydride complex, generated in situ from [{IrCl(cod)}$_2$]–dppp complex and 2-propanol in the presence of Cs$_2$CO$_3$, to α,β-unsaturated carbonyl compound, followed by hydrogen transfer to conjugated double bond, giving a saturated carbonyl compound.

After our finding, Williams et al. reported an indirect Wittig reaction of alcohols by the use of the [{IrCl(cod)}$_2$]/dppp/Cs$_2$CO$_3$ catalytic hydrogen transfer system, which catalyzes the transformation of alcohols to aldehydes.[43] For instance, the reaction of benzyl alcohol with benzyl (triphenylphosphoranylidene)acetate in the presence of catalytic amounts of [{IrCl(cod)}$_2$], dppp, and Cs$_2$CO$_3$ in toluene at 150 °C for 72 h gave benzyl dihydrocinnamate in 79% yield, along with benzyl cinnamate (12%) and benzaldehyde (5%) (Eq. 9).



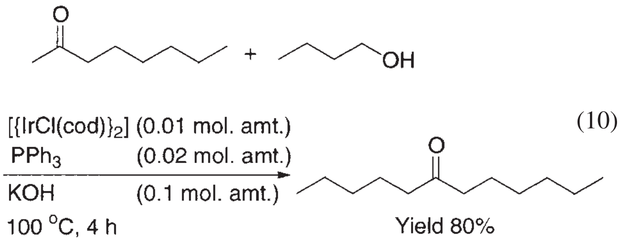
(9)

In addition, Yamaguchi[14d–f] and Hiroi[44] et al. reported that Ir complexes bearing Cp* ligand efficiently catalyze the hydrogen transfer reactions from primary alcohols to acetone and butanone, leading to aldehydes.[45]

3.2 Solvent-Free α-Alkylation of Ketones with Alcohols. α-Alkylation of enolates derived from ketones with alkyl halides is one of the important and frequently used methods for forming a new carbon–carbon bond in organic synthesis.[46] This reaction, however, will inevitably form undesirable waste salts. If the α-alkylation of enolates derived from ketones with alkyl halides can be replaced by the direct reaction of ketones with alcohols, this method would provide a very useful waste-free green route to α-alkylation, which does not produce any side products other than water.

As shown in the preceding section, [{IrCl(cod)}$_2$] catalyzes efficiently the selective hydrogen transfer from alcohols to carbonyl compounds.[41] Williams et al. have also reported an indirect Wittig reaction of alcohols by the use of [{IrCl(cod)}$_2$] which serves as a transfer hydrogenation catalyst of alcohols to aldehydes.[43]

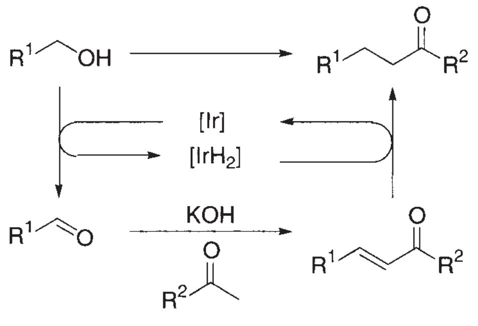
Quite recently, we have successfully achieved the α-alkylation of ketones with alcohols catalyzed by an iridium complex in the presence of a small amount of base.[47] The reaction of 2-octanone with 1-butanol in the presence of [{IrCl(cod)}$_2$] (0.01 molar amount), PPh$_3$ (0.02 molar amount), and KOH (0.01 molar amount) at 100 °C for 4 h without any solvents afforded 6-dodecanone (80%), along with small amounts of 6-dodecanol (2%) and 2-octanol (7%) (Eq. 10).



(10)

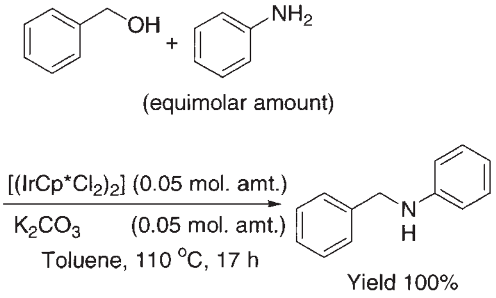
It is interesting to note that the alkylation took place with complete regioselectivity at the less hindered side of 2-octanone. Recently, Cho et al. reported that the α-alkylation of ketones with alcohols in the presence of stoichiometiric amounts of a hydrogen acceptor like 1-dodecene and a base like KOH using dioxane as a solvent is catalyzed by a ruthenium complex.[48] In contrast to the Ru-catalyzed α-alkylation of ketones with alcohols, the Ir-catalyzed reaction took place with a small amount of KOH (0.1 molar amount) in the absence of both a hydrogen acceptor and a solvent. This method provides a very convenient route to aliphatic ketones, to which a carbonyl function can be introduced into the desired position by selecting the ketones and alcohols employed (Table 3).

It seems likely that the reaction proceeds via the following pathway: (i) hydrogen transfer from alcohol to an Ir complex, giving aldehyde and an Ir–dihydride complex; (ii) base-catalyzed aldol condensation between the resulting aldehyde and ketone giving α,β-unsaturated ketone; and (iii) selective hydrogenation of the α,β-unsaturated ketone by an Ir–dihydride complex generated in the reaction course, forming α-alkylated ketone (Scheme 7). Although the in situ generation of an Ir–dihydride complex from [{IrCl(cod)}$_2$], PPh$_3$, and alcohol is not completely confirmed, various iridium dihydride complexes have been prepared and are used in many reactions. Since the present reaction is rationally explained by in situ generation of an Ir–dihydride complex, it seems reasonable to assume the Ir–dihydride complex as a key species in the present reaction.



Scheme 7.

Yamaguchi and co-workers showed that N-alkylation of amines with alcohols was promoted under the influence of [(IrCp*Cl$_2$)$_2$] catalyst combined with K$_2$CO$_3$ in toluene at 110 °C (Eq. 11).[14f] This N-alkylation of amines may proceed in a similar manner to the α-alkylation of aldehydes shown above: (i) dehydrogenation of alcohols to aldehydes, (ii) the formation of imines from aldehydes and amines, and (iii) hydrogenation of imines to amines.



(11)

4. Claisen Rearrangement of Allyl Homoallyl Ethers

Iridium complexes possess efficient potential as catalysts for isomerization of olefinic double bonds. In 1978, Bauday and co-workers showed that treatment of allylic ethers with a catalytic amount of [Ir(cod)(PMePh$_2$)$_2$]PF$_6$ at room temperature afforded E-enol ethers with high stereoselectivity.[49] Allylic alcohols are efficiently isomerized to carbonyl compounds in the presence of IrCl$_3$ in CF$_3$COOH.[50] The iridium-catalyzed double bond migration was successfully applied to the selective synthesis of allylic silanes from homoallylic silanes by Matsuda et al.[51] In recent years, Miyaura et al. studied the stereoselective isomerization of allyl silyl ethers to E- or Z-silyl enol ethers catalyzed by a cationic iridium complex.[52] A polymer-supported iridium was a useful catalyst for isomerization of double bonds.[53] This reaction proceeds with excellent *trans* selectivity and does not need conventional work-up procedures.

The aliphatic Claisen rearrangement of allyl vinyl ethers has been adopted as a valuable synthetic tool for the synthesis of γ,δ-unsaturated carbonyl compounds.[54] Therefore, the Claisen rearrangement is carried out through the in situ generation of allyl vinyl ethers which are derived from β-allyloxyacrylic acids,[55] the reaction of allyl formates with the Tebbe reagent,[56] the acid-catalyzed reaction of diallyl acetals,[57] and the transition metal- or acid-catalyzed transvinylation between alkyl vinyl ethers and allylic alcohols.[58] Diallyl ethers are reported to be converted into γ,δ-unsaturated aldehydes by heating in the presence of [RuCl$_2$(Ph$_3$P)$_3$][59a] or [Ir(C$_8$H$_{12}$)(PMePh$_2$)$_2$]-PF$_6$,[59b] although these reactions must be carried out at a higher temperature (>160 °C).

We found that γ,δ-unsaturated aldehydes can be obtained by treating allyl homoallyl ethers under the influence of [{IrCl(cod)}$_2$] combined with PCy$_3$ and Cs$_2$CO$_3$ through double bond migration, followed by the Claisen rearrangement un-

Table 3. Reaction of Various Ketones with Alcohols Catalyzed by $[\{IrCl(cod)\}_2]$ and KOH[a)]

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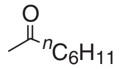
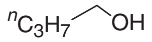
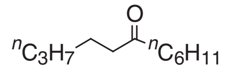
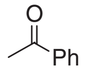
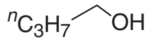
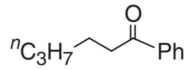
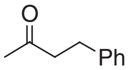
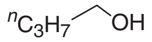
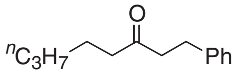
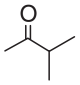
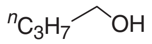
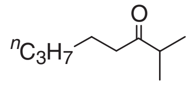
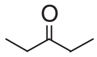
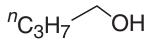
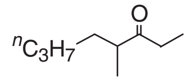
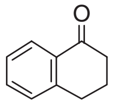
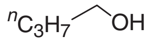
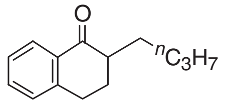
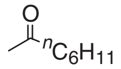
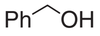
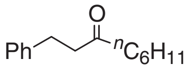
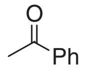
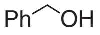
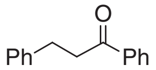
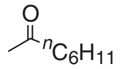
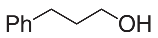
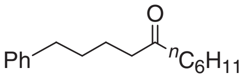
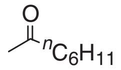
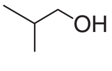
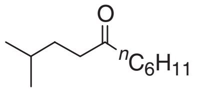
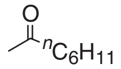
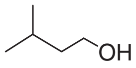
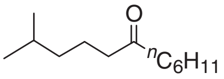
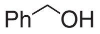
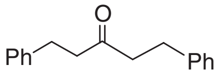
1				80
2[b)]				88
3				71
4				80
5[c)]				47
6[c)]				88
7				81
8				86
9				81
10[d)]				96
11				84
12[e)]				77

a) Ketone (2 mmol) was allowed to react with alcohol (4 mmol) in the presence of $[\{IrCl(cod)\}_2]$ (0.02 mmol), KOH (0.2 mmol), and PPh_3 (0.08 mmol) at 100 °C for 4 h without solvent. b) Butyl alcohol (8 mmol) was used. c) KOH (0.6 mmol) was used. d) KOH (0.4 mmol) was used. e) Benzyl alcohol (8 mmol) was used.

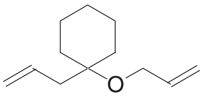
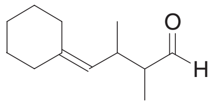
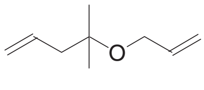
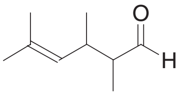
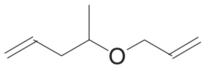
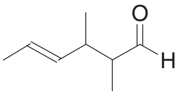
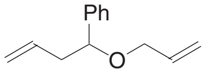
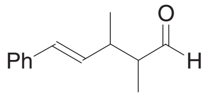
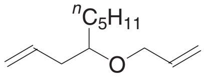
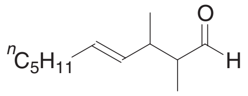
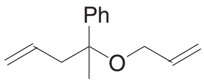
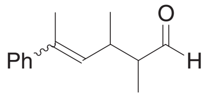
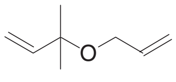
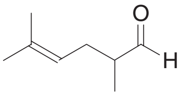
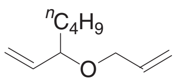
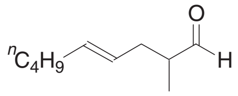
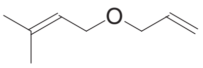
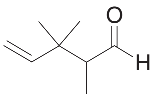
der relatively mild conditions.[60] Thus, a wide variety of allyl homoallyl ethers were converted into the corresponding γ,δ-unsaturated aldehydes in moderate to good yields (Table 4).

It is interesting that 4-allyloxy-1-pentene was converted into *E*-2,3-dimethyl-4-hexenal without the formation of the *Z*-isomer (Run 3). This suggested that the rearrangement took place in regio- and stereoselective fashion to give the sole rearranged product having *E*-geometry. From 4-allyloxy-1-pentene, 3-ethyl-5-hexen-2-one is expected to be formed through an alternative path (b), but no such compound was formed at all (Scheme 8). However, 4-allyloxy-4-phenyl-1-pentene led to a 2:1 stereoisomeric mixture of *E*- and *Z*-2,3-dimethyl-5-phenyl-4-hexenal, whose ratio may be dependent on the free-energy difference between the six-membered transition states (**A**) and (**B**), which are assumed in the common aliphatic Claisen rearrangement (Run 6, Scheme 9). Since the preparation of allyl homoallyl ethers is more easily carried out than that of allyl vinyl ethers, the present method provides a novel route to γ,δ-unsaturated aldehydes which are difficult to prepare by conventional methods. Recently, Dixneuf and co-workers reported that the aliphatic Claisen rearrangement of allyl homoallyl and dially ethers was promoted in the presence of a catalytic amount of a Ru complex, giving γ,δ-unsaturated aldehydes in a manner similar to our Ir-catalyzed reaction.[61]

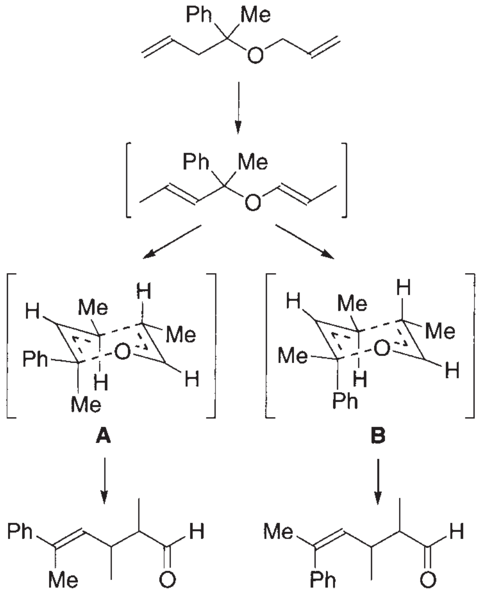
5. Summary

We have shown that [{IrCl(cod)}$_2$] acts as an efficient catalyst for various organic transformations. By the use of [{IrCl(cod)}$_2$] as a key catalyst, efficient and selective carbon–carbon bond-forming reactions, vinyl ether or ester syntheses, hydrogen transfer reactions, α-alkylations of ketones with alcohols, and isomerization–Claisen rearrangement reactions of allyl homoallyl ethers were developed. Such reactions have not been available before this technique was establishied. A new type of C–H bond activation adjacent to the nitrogen atom of imines was catalyzed by [{IrCl(cod)}$_2$], leading to a three-component coupling reaction of aldehydes, amines, and alkynes. The three-component coupling reaction of aliphatic aldehydes, aliphatic amines, and ethyl diazoacetate to the corresponding aziridine derivatives was achieved. The [{IrCl(cod)}$_2$] complex was found to promote a novel transfer vinylation between alcohols and vinyl acetate. The chemoselective reduction of α,β-unsaturated carbonyl compounds to saturated carbonyl compounds using isopropyl alcohol as a hydrogen source has been established by the use of [{IrCl(cod)}$_2$]/dppp/Cs_2CO_3. As an extension of this hydrogen-transfer catalytic system, we developed the α-alkylation of ketones with alcohols catalyzed by [{IrCl(cod)}$_2$]/PPh_3/KOH under solvent-free conditions. The [{IrCl(cod)}$_2$] was applied to aliphatic Claisen rearrangement of allyl homoallyl ethers. The Ir complex possessing a unique catalysis is expected to be extensively used in organic synthesis.

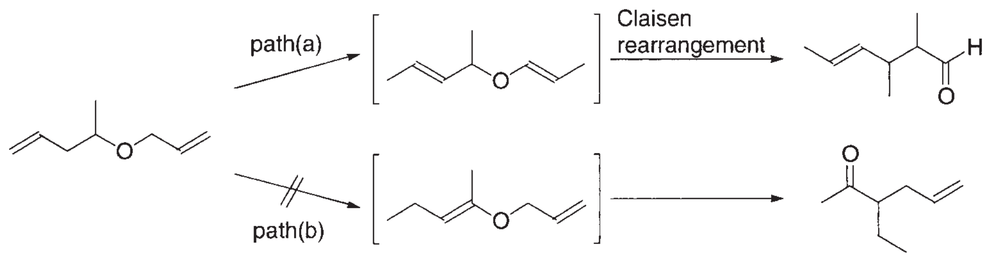
Table 4. Claisen Rearrangement of Various Allyl Homoallyl Ethers and Diallyl Ethers Catalyzed by [{IrCl(cod)}$_2$][a)]

Run	Substrate	Product	Yield /%
1			74
2			68
3			78
4			81
5			72
6			81[b)]
7			78
8			48
9[c)]			78

a) Substrate (0.5 mmol) was allowed to react in the presence of catalytic amounts of [{IrCl(cod)}$_2$] (0.005 mmol), PCy_3 (0.01 mmol), and Cs_2CO_3 (0.005 mmol) in toluene (0.5 mL) at 100 °C for 15 h under Ar. b) The ratio of E-isomer/Z-isomer was 2/1. c) The reaction was carried out in p-xylene at 140 °C.



Scheme 9.



Scheme 8.

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References

1 a) R. H. Crabtree and G. E. Morris, *J. Organomet. Chem.*, **135**, 135 (1977). b) R. H. Crabtree, H. Felkin, and G. E. Morris, *J. Organomet. Chem.*, **141**, 205 (1977). c) R. H. Crabtree, *Acc. Chem. Res.*, **12**, 331 (1979).

2 G. Stork and D. E. Kahne, *J. Am. Chem. Soc.*, **105**, 1072 (1983).

3 a) A. Lightfoot, P. Schnider, and A. Pfaltz, *Angew. Chem., Int. Ed.*, **37**, 2897 (1998). b) S. Kainz, A. Brinkmann, W. Leitner, and A. Pfaltz, *J. Am. Chem. Soc.*, **121**, 6421 (1999). c) L. D. Vázquez-Serrano, B. T. Owens, and J. M. Buriak, *Chem. Commun.*, **2002**, 2518. d) M. C. Perry, X. Cui, M. T. Powell, D.-R. Hou, J. H. Reibenspies, and K. Burgess, *J. Am. Chem. Soc.*, **125**, 113 (2003). e) W.-B. Wang, S.-M. Lu, P.-Y. Yang, X.-W. Han, and Y.-G. Zhou, *J. Am. Chem. Soc.*, **125**, 10536 (2003). f) A. Pfaltz, J. Blankenstein, R. Hilgraf, E. Hormann, S. Mclntyre, M. Steven, F. Menges, M. Schonleber, S. P. Smidt, B. Wustenberg, and N. Zimmermann, *Adv. Synth. Catal.*, **345**, 33 (2003).

4 N. Chatani, S. Ikeda, K. Ohe, and S. Murai, *J. Am. Chem. Soc.*, **114**, 9710 (1992).

5 N. Chatani, S. Yamaguchi, Y. Fukumoto, and S. Murai, *Organometallics*, **14**, 4418 (1995).

6 C. Jun, Z. Lu, and R. H. Crabtree, *Tetrahedron Lett.*, **33**, 7119 (1992).

7 a) R. Takeuchi and M. Kashio, *Angew. Chem., Int. Ed. Engl.*, **36**, 263 (1997). b) J. P. Janssen and G. Helmchen, *Tetrahedron Lett.*, **38**, 8025 (1997). c) R. Takeuchi and M. Kashi, *J. Am. Chem. Soc.*, **120**, 8647 (1998). d) M. Murakami, K. Itami, M. Ubukata, I. Tsuji, and Y. Ito, *J. Org. Chem.*, **63**, 4 (1998). e) T. Matsumoto, D. J. Taube, R. A. Periana, H. Taube, and H. Yoshida, *J. Am. Chem. Soc.*, **122**, 7414 (2000). f) T. Shibata and K. Takagi, *J. Am. Chem. Soc.*, **122**, 9852 (2000). g) I. Matsuda, Y. Hasegawa, T. Makino, and K. Itoh, *Tetrahedron Lett.*, **41**, 1405 (2000). h) I. Matsuda, Y. Hasegawa, T. Makino, and K. Itoh, *Tetrahedron Lett.*, **41**, 1409 (2000). i) R. Takeuchi, S. Tanaka, and S. Nakaya, *Tetrahedron Lett.*, **42**, 2991 (2001). j) N. Chatani, H. Inoue, T. Morimoto, T. Muto, and S. Murai, *J. Org. Chem.*, **66**, 4433 (2001). k) T. Shibata, K. Yamashita, H. Ishida, and K. Takagi, *Org. Lett.*, **3**, 1217 (2001). l) C. Zhao, M. O. Duffey, S. J. Taylor, and J. P. Morken, *Org. Lett.*, **3**, 1829 (2001). m) R. Takeuchi, *Synlett*, **2002**, 1954. n) T. Shibata, S. Kadowaki, M. Hirase, and K. Takagi, *Synlett*, **2003**, 573. o) T. Koike, X. Du, T. Sanada, Y. Danda, and A. Mori, *Angew. Chem., Int. Ed.*, **42**, 89 (2003).

8 a) R. Takeuchi and N. Shiga, *Org. Lett.*, **1**, 265 (1999). b) R. Takeuchi, N. Ue, K. Tanabe, K. Yamashita, and N. Shiga, *J. Am. Chem. Soc.*, **123**, 9525 (2001). c) T. Ohmura and J. F. Hartwig, *J. Am. Chem. Soc.*, **124**, 15164 (2002). d) H. Miyabe, K. Yoshida, A. Matsumura, M. Yamauchi, and Y. Takemoto, *Synlett*, **2003**, 567. e) H. Miyabe, K. Yoshida, Y. Kobayashi, A. Matsumura, and Y. Takemoto, *Synlett*, **2003**, 1031. f) F. López, T. Ohmura, and J. F. Hartwig, *J. Am. Chem. Soc.*, **125**, 3426 (2003).

9 a) T. Ishiyama, J. Takagi, J. F. Hartwig, and N. Miyaura, *Angew. Chem., Int. Ed.*, **41**, 3056 (2002). b) T. Ishiyama, J. Takagi, K. Ishida, and N. Miyaura, *J. Am. Chem. Soc.*, **124**, 390 (2002). c) J. Takagi, K Sato, J. F. Hartwig, T. Ishiyama, and N. Miyaura, *Tetrahedron Lett.*, **43**, 5649 (2002). d) R. E. Maleczka, Jr., F. Shi, D. Holmes, and M. R. Smith, III, *J. Am. Chem. Soc.*, **125**, 7792 (2003).

10 a) M. Gupta, W. C. Kaska, and C. M. Jensen, *Chem. Commun.*, **1997**, 461. b) F. Liu, E. B. Pak, B. Singh, C. M. Jensen, and A. S. Goldman, *J. Am. Chem. Soc.*, **121**, 4086 (1999). c) K. B. Renkema, Y. V. Kissin, and A. S. Goldman, *J. Am. Chem. Soc.*, **125**, 7770 (2003).

11 a) R. Dorta and A. Togni, *Chem. Commun.*, **2003**, 760. b) M. J. Hickey, J. R. Jones, L. P. Kingston, W. J. S. Lockley, A. N. Mather, B. M. McAuley, and D. J. Wilkinson, *Tetrahedron Lett.*, **44**, 3959 (2003).

12 a) H. Takaya, T. Naota, and S.-I. Murahashi, *J. Am. Chem. Soc.*, **120**, 4244 (1998). b) S. Murahashi and H. Takaya, *Acc. Chem. Res.*, **33**, 225 (2000).

13 a) T. Satoh, Y. Nishinaka, M. Miura, and M. Nomura, *Chem. Lett.*, **1999**, 615. b) Y. Nishinaka, T. Satoh, M. Miura, H. Morisaka, M. Nomura, H. Matsui, and C. Yamaguchi, *Bull. Chem. Soc. Jpn.*, **74**, 1727 (2001). c) T. Yasukawa, T. Satoh, M. Miura, and M. Nomura, *J. Am. Chem. Soc.*, **124**, 12680 (2002).

14 a) D. Carmona, F. J. Lahoz, S. Elipe, L. A. Oro, M. P. Lamata, F. Viguri, C. Mir, C. Cativiela, and M. P. L.-R. de Víu, *Organometallics*, **17**, 2986 (1998). b) Z. Hou, T. Koizumi, A. Fujita, H. Yamazaki, and Y. Wakatsuki, *J. Am. Chem. Soc.*, **123**, 5812 (2001). c) S. R. Klei, J. T. Golden, T. D. Tilley, and R. G. Bergman, *J. Am. Chem. Soc.*, **124**, 2092 (2002). d) K. Fujita, S. Furukawa, and R. Yamaguchi, *J. Organomet. Chem.*, **649**, 289 (2002). e) K. Fujita, K. Yamamoto, and R. Yamaguchi, *Org. Lett.*, **4**, 2691 (2002). f) K. Fujita, Z. Li, N. Ozeki, and R. Yamaguchi, *Tetrahedron Lett.*, **44**, 2687 (2003).

15 S. Sakaguchi, T. Kubo, and Y. Ishii, *Angew. Chem., Int. Ed.*, **40**, 2534 (2001).

16 a) "Activation of Unreactive Bonds and Organic Synthesis," ed by S. Murai, Springer, New York (1999). b) G. Dyker, *Angew. Chem., Int. Ed.*, **38**, 1698 (1999). c) A. Sen, *Acc. Chem. Res.*, **31**, 550 (1998). d) B. A. Arndtsen, R. G. Bergman, T. A. Mobley, and T. H. Peterson, *Acc. Chem. Res.*, **28**, 154 (1995). e) A. D. Ryabov, *Chem. Rev.*, **90**, 403 (1990).

17 T. Ohmura, S. Yarozuya, Y. Yamamoto, and N. Miyaura, *Organometallics*, **19**, 365 (2000).

18 C. Fischer and E. M. Carreira, *Org. Lett.*, **3**, 4319 (2001).

19 a) J. S. Brimacombe, R. Hanna, and L. C. N. Tucker, *J. Chem. Soc., Perkin Trans. 1*, **1983**, 2277. b) J. Martens and M. Scheunemann, *Tetrahedron Lett.*, **32**, 1417 (1991). c) D. Tanner, *Angew. Chem., Int. Ed. Engl.*, **33**, 599 (1994).

20 a) K. B. Hansen, N. S. Finney, and E. N. Jacobsen, *Angew. Chem., Int. Ed. Engl.*, **34**, 676 (1995). b) Z. Zhu and J. H. Espenson, *J. Org. Chem.*, **60**, 7090 (1995). c) Z. Zhu and J. H. Espenson, *J. Am. Chem. Soc.*, **118**, 9901 (1996). d) L. Casarrubios, J. A Pérez, M. Brookhart, and J. L. Templeton, *J. Org. Chem.*, **61**, 8358 (1996). e) V. K. Aggarwal, A. Thompson, R. V. H. Jones, and M. C. H. Standen, *J. Org. Chem.*, **61**, 8386 (1996). f) K. G. Rasmuussen and K. A. Jørgensen, *J. Chem. Soc., Perkin Trans. 1*, **1997**, 1287. g) M. F. Mayer and M. M. Hossain, *J. Org. Chem.*, **63**, 6839 (1998). h) K. Juhl, R. G. Hazell, and K. A. Jørgensen, *J. Chem. Soc., Perkin Trans. 1*, **1999**, 2293.

21 T. Kubo, S. Sakaguchi, and Y. Ishii, *Chem. Commun.*, **2000**, 625.

22 S. Nagayama and S. Kobayashi, *Chem. Lett.*, **1998**, 685.

23 a) H. Kanai and M. Okada, *Chem. Lett.*, **1975**, 167. b) H.

Kanai and K. Ishii, *Bull. Chem. Soc. Jpn.*, **54**, 1015 (1981). c) G. Wilke, *Angew. Chem., Int. Ed. Engl.*, **27**, 185 (1988). d) R. J. McKinney and M. C. Colton, *Organometallics*, **5**, 1080 (1986). e) R. J. McKinney, *Organometallics*, **5**, 1752 (1986). f) M. A. Bennett, *Organometallics*, **14**, 2565 (1995). g) T. Alderson, E. T. Jenner, and R. V. J. Lindsey, *J. Am. Chem. Soc.*, **87**, 5638 (1965). h) G. I. Nikishin, I. P. Kovalev, and A. V. Ignatenko, *Tetrahedron Lett.*, **32**, 1077 (1991). i) M. Brookhart and S. Sabo-Etienne, *J. Am. Chem. Soc.*, **113**, 2777 (1991). j) M. Brookhart and E. Hauptman, *J. Am. Chem. Soc.*, **114**, 4437 (1992). k) E. Hauptman, S. S. Etienne, P. S. White, M. Brookhart, J. M. Garner, P. J. Fagan, and J. C. Calabrese, *J. Am. Chem. Soc.*, **116**, 8038 (1994). l) G. Oehme and H. Pracejus, *Tetrahedron Lett.*, **20**, 343 (1979). m) W. A. Nugent and F. W. J. Hobbs, *J. Org. Chem.*, **48**, 5364 (1983). n) I. Tkatchenko, D. Neibecker, and P. Grenouillet, *Organometallics*, **3**, 1130 (1984). o) I. Guibert, D. Neibecker, and I. Tkatchenko, *J. Chem. Soc., Chem. Commun.*, **1989**, 1850.

24 H. Nakagawa, S. Sakaguchi, and Y. Ishii, *Chem. Commun.*, **2003**, 502.

25 W. Reppe, *Justus Liebigs Ann. Chem.*, **601**, 84 (1956).

26 a) W. H. Watannabe and L. E. Conlon, *J. Am. Chem. Soc.*, **79**, 2828 (1957). b) H. Lüssi, *Helv. Chim. Acta*, **49**, 1681 (1966).

27 a) F. Nerdel, J. Buddrus, W. Brodowski, P. Hentschel, D. Klamar, and P. Weyerstahl, *Justus Liebigs Ann. Chem.*, **710**, 36 (1967). b) S. J. Rhoads, J. K. Chattopadhyay, and E. E. Waali, *J. Org. Chem.*, **35**, 3352 (1970).

28 a) J. Yamawaki, T. Kawate, T. Ando, and T. Hanafusa, *Bull. Chem. Soc. Jpn.*, **56**, 1885 (1983). b) K. Mizuno, Y. Kimura, and Y. Otsuji, *Synthesis*, **1979**, 688.

29 R. C. Larock, "Comprehensive Organic Transformations," 2nd ed, Wiley-VCH, New York (1999), pp. 222 and 225–226.

30 A. Alexakis, G. Cahiez, J. F. Normant, and J. Villieras, *Bull. Soc. Chim. Fr.*, **1977**, 693.

31 Y. Okimoto, S. Sakaguchi, and Y. Ishii, *J. Am. Chem. Soc.*, **124**, 1590 (2002).

32 M. Bosch and M. Schlaf, *J. Org. Chem.*, **68**, 5225 (2003).

33 a) E. R. Murray and C. M. Lincoln, *Catal. Today*, **13**, 93 (1992). b) P. M. Henry, *Acc. Chem. Res.*, **6**, 16 (1973).

34 H. Nakagawa, Y. Okimoto, S. Sakaguchi, and Y. Ishii, *Tetrahedron Lett.*, **44**, 103 (2003).

35 L. J. Goossen, J. Paetzold, and D. Koley, *Chem. Commun.*, **2003**, 706.

36 a) T. Mizugaki, Y. Kanayama, K. Ebitani, and K. Kaneda, *J. Org. Chem.*, **63**, 2378 (1998). b) C. Bianchini, M. Peruzzini, E. Farnetti, J. Kašper, and M. Graziani, *J. Organomet. Chem.*, **488**, 91 (1995). c) S. Bhaduri and K. Sharma, *J. Chem. Soc., Chem. Commun.*, **1988**, 173. d) K. Yoshinaga, T. Kito, and K. Ohkubo, *Bull. Chem. Soc. Jpn.*, **56**, 1786 (1983).

37 a) G. Zassinovich and G. Mestroni, *Chem. Rev.*, **92**, 1051 (1992). b) C. Bianchini, E. Farnetti, M. Graziani, G. Nardin, A. Vacca, and F. Zanobini, *J. Am. Chem. Soc.*, **112**, 9190 (1990). c) S. De Martin, G. Zassinovich, and G. Mestroni, *Inorg. Chim. Acta*, **174**, 9 (1990). d) B. B. James and H. R. Morris, *J. Chem. Soc., Chem. Comm.*, **1978**, 929.

38 a) M. Saburi, M. Ohnuki, M. Ogasawara, T. Takahashi, and Y. Uchida, *Tetrahedron Lett.*, **33**, 5783 (1992). b) Y. Sasson and J. Blum, *J. Org. Chem.*, **40**, 1887 (1975). c) Y. Sasson, M. Cohen, and J. Blum, *Synthesis*, **1973**, 359. d) Y. Sasson and J. Blum, *Tetrahedron Lett.*, **12**, 2167 (1971).

39 S. Bhaduri, K. Sharma, and D. Mukesh, *J. Chem. Soc., Dalton Trans.*, **1992**, 77.

40 a) D. Beaupere, P. Bauer, L. Nadjo, and R. Uzan, *J. Organomet. Chem.*, **238**, C12 (1982). b) D. Beaupere, L. Nadjo, R. Uzan, and P. Bauer, *J. Mol. Catal.*, **18**, 73 (1983).

41 S. Sakaguchi, T. Yamaga, and Y. Ishii, *J. Org. Chem.*, **66**, 4710 (2001).

42 K. Tani, A. Iseki, and T. Yamagata, *Chem. Commun.*, **1999**, 1821.

43 M. G. Edwards and J. M. J. Williams, *Angew. Chem., Int. Ed.*, **41**, 4740 (2002).

44 a) T. Suzuki, K. Morita, M. Tsuchida, and K. Hiroi, *Org. Lett.*, **4**, 2361 (2002). b) T. Suzuki, K. Morita, M. Tsuchida, and K. Hiroi, *J. Org. Chem.*, **68**, 1601 (2003). c) T. Suzuki, K. Morita, Y. Matsuo, and K. Hiroi, *Tetrahedron Lett.*, **44**, 2003 (2003).

45 Other transfer hydrogenations of carbonyl compounds by iridium complexes: a) A. C. Hillier, H. M. Lee, E. D. Stevens, and S. P. Nolan, *Organometallics*, **20**, 4246 (2001). b) M. Albrecht, J. R. Miecznikowski, A. Samuel, J. W. Faller, and R. H. Crabtree, *Organometallics*, **21**, 3596 (2002). c) T. Abura, S. Ogo, Y. Watanabe, and S. Fukuzumi, *J. Am. Chem. Soc.*, **125**, 4149 (2003). Asymmetric transfer hydrogenation of carbonyl compounds: d) S.-I. Inoue, K. Nomura, S. Hashiguchi, R. Noyori, and Y. Izawa, *Chem. Lett.*, **1997**, 957. e) Y. Nishibayashi, J. D. Singh, Y. Arikawa, S. Uemura, and M. Hidai, *J. Organomet. Chem.*, **531**, 13 (1997). f) K. Mashima, T. Abe, and K. Tani, *Chem. Lett.*, **1998**, 1199. g) K. Murata, T. Ikariya, and R. Noyori, *J. Org. Chem.*, **64**, 2186 (1999).

46 D. Carine, "Carbon-Carbon Bond Formation," ed by R. L. Augustine, Marcel Dekker Inc., New York (1989), Vol. 1, pp. 85–352.

47 K. Taguchi, H. Nakagawa, T. Hirabayashi, S. Sakaguchi, and Y. Ishii, *J. Am. Chem. Soc.*, **126**, 72 (2004).

48 C. S. Cho, B. T. Kim, T. Kim, and S. C. Shim, *Tetrahedron Lett.*, **43**, 7987 (2002).

49 B. D. Baudry, M. Ephritikhine, and H. Felkin, *J. Chem. Soc., Chem. Commun.*, **1978**, 694.

50 a) W. Strohmeier and L. Weigelt, *J. Organomet. Chem.*, **86**, C17 (1975). b) Review: R. Uma, C. Crévisy, and R. Grée, *Chem. Rev.*, **103**, 27 (2003), and references cited therein.

51 I. Matsuda, T. Kato, S. Sato, and Y. Izumi, *Tetrahedron Lett.*, **27**, 5747 (1986).

52 a) T. Ohmura, Y. Shirai, Y. Yamamoto, and N. Miyaura, *Chem. Commun.*, **1998**, 1337. b) T. Ohmura, Y. Yamamoto, and N. Miyaura, *Organometallics*, **18**, 413 (1999). c) Y. Yamamoto, T. Miyairi, T. Ohmura, and N. Miyaura, *J. Org. Chem.*, **64**, 296 (1999).

53 I. R. Baxendale, A. Lee, and S. V. Ley, *Synlett*, **2002**, 526.

54 a) S. J. Rohads and N. R. Raulins, *Org. React.*, **22**, 1 (1975). b) F. E. Ziegler, *Acc. Chem. Res.*, **10**, 277 (1977). c) R. P. Lutz, *Chem. Rev.*, **84**, 205 (1984). d) F. E. Ziegler, *Chem. Rev.*, **88**, 1423 (1988).

55 a) G. H. Büchi and D. E. Vogel, *J. Org. Chem.*, **48**, 5408 (1983). b) D. E. Vogel and G. H. Büchi, *Org. Synth.*, **66**, 29 (1987).

56 C. J. Burrows and B. K. Carpenter, *J. Am. Chem. Soc.*, **103**, 6983 (1981).

57 a) C. Hurd and M. Pollack, *J. Am. Chem. Soc.*, **60**, 1905 (1938). b) N. B. Lorette and W. L. Howard, *J. Org. Chem.*, **26**, 3112 (1961). c) K. C. Brannock, *J. Am. Chem. Soc.*, **81**, 3379 (1959). d) D. S. Sethi and P. Yates, *J. Am. Chem. Soc.*, **95**, 3820 (1973).

58 a) W. H. Watanabe and L. E. Condon, *J. Am. Chem. Soc.*, **79**, 2828 (1957). b) D. J. Faulkner and M. R. Petersen, *J. Am. Chem. Soc.*, **95**, 553 (1973). c) R. E. Ireland and D. J. Dawson, *Org. Synth.*, Coll. Vol. **VI**, 298 (1988). d) K. Mikami, K.

Takahashi, and T. Nakai, *Tetrahedron Lett.*, **28**, 5879 (1987). e) M. Sugiura, M. Yanagisawa, and T. Nakai, *Synlett*, **1995**, 447.

59 a) J. M. Reuter and R. G. Salomon, *J. Org. Chem.*, **42**, 3360 (1977). b) R. S. Iyer, M. E. Kobierski, and R. G. Salomon, *J. Org. Chem.*, **59**, 6038 (1994).

60 T. Higashino, S. Sakaguchi, and Y. Ishii, *Org. Lett.*, **2**, 4193 (2000).

61 J. L. Nôtre, L. Brissieux, D. Sémeril, C. Bruneau, and P. H. Dixneuf, *Chem. Commun.*, **2002**, 1772.

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