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Rhodium-Catalyzed Allylation of Aldehydes with Homoallylic Alcohols by Retroallylation and Isomerization to Saturated Ketones with Conventional or Microwave Heating

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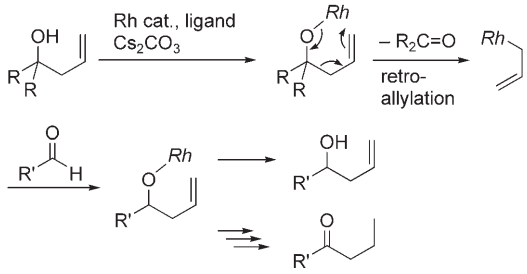
Abstract: The treatment of an aldehyde with a tertiary homoallylic alcohol at 100–250 °C in the presence of cesium carbonate and a rhodium catalyst leads to allyl transfer from the homoallylic alcohol to the aldehyde. The process includes Rh-mediated retroallylation to form an allyl rhodium species as the key intermediate. The homoallylic alcohol formed initially through allyl transfer is converted under the reaction conditions into the corresponding saturated ketone when bulky ligands are used. Microwave heating at 250 °C accelerates the reaction significantly.

Keywords: allylation · C–C activation · isomerization · retro reactions · rhodium

Introduction

Metal-mediated carbon–carbon bond-cleavage reactions have attracted increasing attention in organic synthesis and organometallic chemistry.[1] The metal-mediated retroallylation of homoallylic alcohols, for example, is a useful method for generating allyl metal reagents.[2] Recently, we reported that retroallylation takes place under rhodium catalysis (Scheme 1).[3,4] The allyl rhodium species thus formed was found to allylate carbonyl compounds, as a rare example of nucleophilic allylation with allyl rhodium species.[5] The allylated intermediates are finally converted into the corresponding saturated ketones when the rhodium catalyst contains a bulky phosphine ligand. Herein, we report details of the reaction and describe improved reaction conditions, under which microwave heating is used to accelerate the formation of the saturated ketones.



Scheme 1. Rhodium-catalyzed allylation of aldehydes with homoallylic alcohols by retroallylation.

Results and Discussion

The treatment of benzaldehyde (**1a**; 0.5 mmol) with the homoallylic alcohol **2a** (1.0 mmol) in the presence of [{RhCl(cod)}$_2$] (2.5 mol %), PMe_3 (10 mol %), and cesium carbonate (15 mol %) in dioxane (5.0 mL) at reflux for 8 h provided 2-methyl-1-phenyl-3-buten-1-ol (**3a**) in 58 % yield (*erythro*/*threo*[6] = 49:51; Table 1, entry 1). We propose that initial ligand exchange promoted by cesium carbonate between the rhodium catalyst and **2a** provides the intermediate **4** (Scheme 2). The retroallylation of **4** generates a σ-crotyl rhodium species,[7] which may be in equilibrium with the π-crotyl rhodium species under the reaction conditions. The allyl rhodium intermediate reacts at the more substituted carbon atom[5b] with benzaldehyde to yield the rhodium ho-

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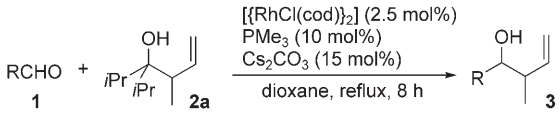
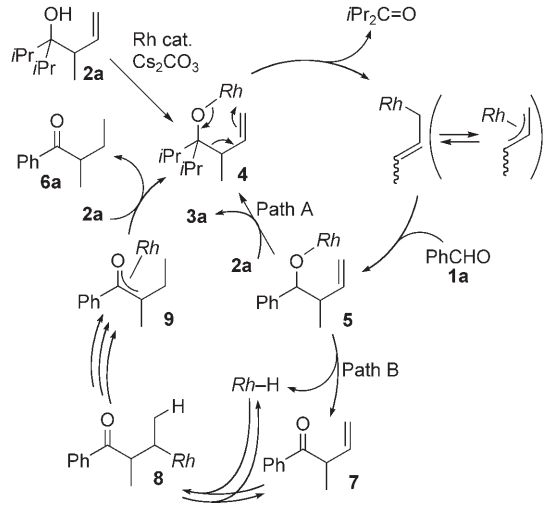
Table 1. Rhodium-catalyzed crotylation of aromatic aldehydes with **2a**.



Entry	R	Yield of **3** [%]	*erythro*/*threo*
1	Ph (**a**)	58	49:51
2	4-MeC_6H_4 (**b**)	49	54:46
3	4-$CF_3C_6H_4$ (**c**)	44	56:44
4	4-$MeOC_6H_4$ (**d**)	34	52:48
5	4-ClC_6H_4 (**e**)	59	58:42
6	4-$PhCOC_6H_4$ (**f**)	58	56:44
7[a]	4-$MeOCOC_6H_4$ (**g**)	59	56:44

[a] Cs_2CO_3 (30 mol%) was used. cod = 1,5-cyclooctadiene.



Scheme 2. Proposed reaction mechanism.

moallyloxide **5**, which undergoes protonolysis with **2a** to yield **3a** and regenerate **4** (path A).

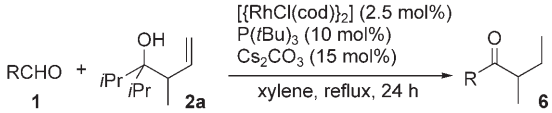
Moderate to good yields were generally observed for the formation of compounds **3** (Table 1), although the crotylation reaction of electron-rich **1d** gave the product in poorer yield (Table 1, entry 4). The presence of a chlorine substituent on the aromatic ring did not prevent the reaction (Table 1, entry 5), and ketone and ester functionalities were compatible with the reaction conditions (Table 1, entries 6 and 7). Unfortunately, no stereoselectivity was observed in any of the reactions.

Abstract in Japanese:

炭酸セシウムとロジウム触媒存在下アルデヒドとホモアリルアルコールの混合物を加熱するとホモアリルアルコールからアルデヒドへのアリル基移動反応がおこる。この過程ではロジウムアルコキシドのレトロアリル化によるアリルロジウム中間体の発生が鍵である。アリル基の移動により生じるホモアリロキシロジウムは二重結合の異性化を経て対応する飽和ケトンとなる。マイクロ波照射下 250°C で反応を行うと、反応時間を著しく短縮することが可能である。

The use of xylene as the solvent and $P(tBu)_3$ as the ligand led to a drastic change in the course of the reaction. The treatment of benzaldehyde (**1a**; 0.5 mmol) with the homoallylic alcohol **2a** (1.0 mmol) in the presence of catalytic amounts of $[\{RhCl(cod)\}_2]$, $P(tBu)_3$, and cesium carbonate in xylene at reflux for 24 h provided 2-methyl-1-phenyl-1-butanone (**6a**) in 70% yield (Table 2). Both electron-rich (Table 2, entry 4) and electron-deficient aromatic aldehydes (Table 2, entries 3, 6, and 7) were transformed into the corresponding ketones in satisfactory yields.

Table 2. Rhodium-catalyzed crotylation of aromatic aldehydes with **2a** followed by isomerization to saturated ketones.



Entry	R	Yield of **6** [%]
1[a]	Ph (**a**)	70[b]
2	4-MeC_6H_4 (**b**)	49
3[c]	4-$CF_3C_6H_4$ (**c**)	50[b]
4	4-$MeOC_6H_4$ (**d**)	52[b]
5	4-ClC_6H_4 (**e**)	51[b]
6	4-$PhCOC_6H_4$ (**f**)	48[d]
7	4-$MeOCOC_6H_4$ (**g**)	59[e]

[a] Cs_2CO_3 (5 mol%) was used. [b] Yield determined by NMR spectroscopy. [c] The reaction was carried out in toluene at reflux for 24 h. [d] 1-(4-Benzoylphenyl)-1-pentanone was obtained in 3% yield. [e] 1-(4-Methoxycarbonylphenyl)-1-pentanone was obtained in 3% yield.

We rationalize the formation of **6a** as follows (Scheme 2): Owing to the steric effect of $P(tBu)_3$, the protonolysis of **5** with **2a** (path A) is so slow that β-hydride elimination takes place (path B) to yield **7** with concomitant formation of rhodium hydride. Hydrorhodation of the alkene in **7** then affords **8**, which undergoes iterative β-elimination/hydrorhodation[8] to yield the oxa-π-allylrhodium intermediate **9**. Protonolysis of **9** with **2a** provides **6a** and **4** to complete the catalytic cycle.

The reaction of the homoallylic alcohol **2b** was sluggish and provided **6a** in only 26% yield (Scheme 3). A small amount of **10** was also formed. The formation of **10** was not observed in the reactions in Table 2. These results indicate that the allyl rhodium species is formed through a retroallylation mechanism. The retroallylation of **11** would yield (1-methyl-2-propenyl)rhodium, some of which would react with **1a** to yield **12** before isomerizing to π- and σ-crotylrhodium. The alkoxide **12** would be converted into **10**. The π- and/or σ-crotylrhodium intermediates would react with **1a** to afford **5** and then **6a**. The equilibrium between (1-methyl-2-propenyl)rhodium, π-crotylrhodium, and σ-crotylrhodium is probably shifted towards the two crotylrhodium species.

We studied the sequential methallylation–isomerization of an array of aldehydes (Table 3). The generation of methallylrhodium was facile, and the products **13** were generally formed in good yield. Both aliphatic and aromatic aldehydes

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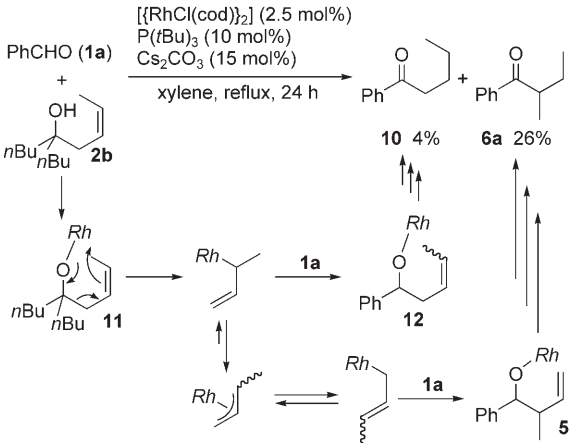
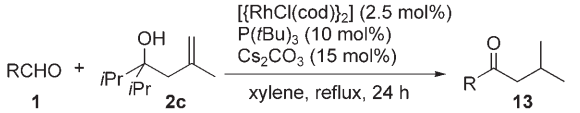


Scheme 3. Plausible mechanism for the rhodium-catalyzed reaction with **2b**.

Table 3. Rhodium-catalyzed methallylation of aldehydes with **2c** followed by isomerization to saturated ketones.

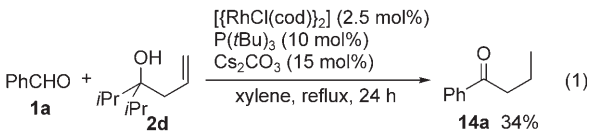


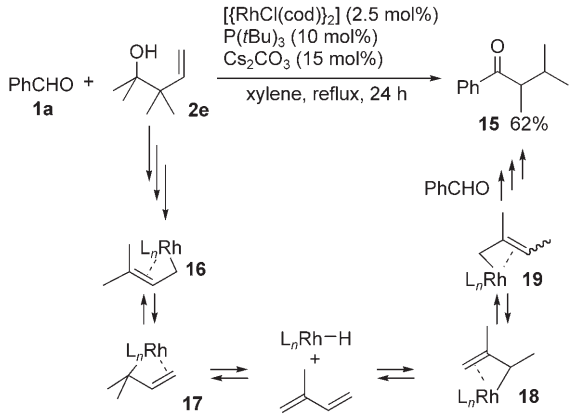
Entry	R	Yield of **13** [%]
1	Ph (**a**)	83
2	4-MeC_6H_4 (**b**)	66
3	4-$CF_3C_6H_4$ (**c**)	65
4	4-$MeOC_6H_4$ (**d**)	77
5	4-ClC_6H_4 (**e**)	54
6	4-$PhCOC_6H_4$ (**f**)	66
7	4-$MeOCOC_6H_4$ (**g**)	68
8	*n*-$C_{11}H_{23}$ (**h**)	70[a]

[a] Yield determined by NMR spectroscopy.

participated in the reaction. Dodecanal (**1h**) was converted into the corresponding saturated ketone **13h** in 70% yield (Table 3, entry 8).

The transfer of the parent allyl group and the prenyl group was also examined. The sequential allylation–isomerization of benzaldehyde (**1a**) with the homoallylic alcohol **2d** led to **14a** in low yield [Eq. (1)]. The reaction of **1a** with **2e** provided the unexpected ketone **15** in 62% yield (Scheme 4). We propose the following mechanism for the formation of **15**: The σ-prenylrhodium intermediate **16** generated by retroprenylation does not react readily with **1a** as a result of steric repulsion at the highly substituted carbon atom. Accordingly, **16** isomerizes to **17**, from which β-H elimination occurs to give a rhodium hydride and isoprene. Subsequent hydrorhodation of isoprene leads to **18** and **19**, and the latter intermediate reacts with **1a** to furnish **15**.

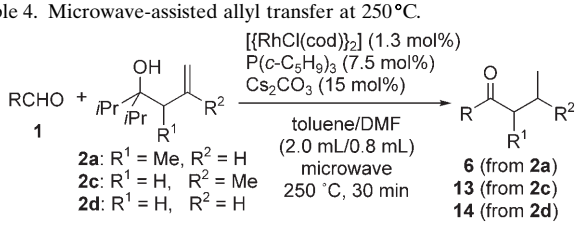




Scheme 4. Attempted prenylation.

It is well-known that microwave heating accelerates organic reactions.[9] Such an effect was observed for the allyl-transfer reaction (Table 4). Under microwave irradiation, the reactions were complete within 30 min to afford the corresponding ketones in comparable yields to those observed

Table 4. Microwave-assisted allyl transfer at 250 °C.



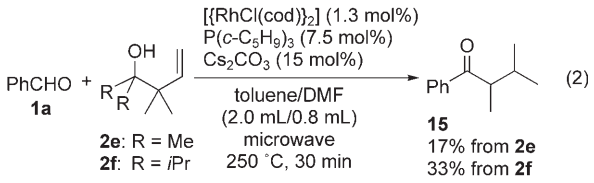
Entry	R	**2**	Product	Yield [%]
1	Ph (**a**)	**2a**	**6a**	90[a]
2	4-MeC_6H_4 (**b**)	**2a**	**6b**	72[a]
3	4-$CF_3C_6H_4$ (**c**)	**2a**	**6c**	67[a]
4	4-$MeOC_6H_4$ (**d**)	**2a**	**6d**	87[a]
5	4-ClC_6H_4 (**e**)	**2a**	**6e**	55[a]
6	4-(4-MeC_6H_4CO)C_6H_4 (**i**)	**2a**	**6i**	58[a]
7	4-$MeOCOC_6H_4$ (**g**)	**2a**	**6g**	41[a]
8	*n*-$C_{11}H_{23}$ (**h**)	**2a**	**6h**	64[a]
9	Ph (**a**)	**2c**	**13a**	91
10	4-MeC_6H_4 (**b**)	**2c**	**13b**	86
11	4-$CF_3C_6H_4$ (**c**)	**2c**	**13c**	64
12	4-$MeOC_6H_4$ (**d**)	**2c**	**13d**	74
13	4-ClC_6H_4 (**e**)	**2c**	**13e**	84
14	4-(4-MeC_6H_4CO)C_6H_4 (**i**)	**2c**	**13i**	48
15	4-$MeOCOC_6H_4$ (**g**)	**2c**	**13g**	40
16	*n*-$C_{11}H_{23}$ (**h**)	**2c**	**13h**	67
17	*c*-C_6H_{11} (**j**)	**2c**	**13j**	68
18	*t*Bu (**k**)	**2c**	**13k**	≈5[b]
19	Ph (**a**)	**2d**	**14a**	87
20	4-MeC_6H_4 (**b**)	**2d**	**14b**	90
21	4-$CF_3C_6H_4$ (**c**)	**2d**	**14c**	77
22	4-$MeOC_6H_4$ (**d**)	**2d**	**14d**	75
23	4-ClC_6H_4 (**e**)	**2d**	**14e**	68
24	4-(4-MeC_6H_4CO)C_6H_4 (**i**)	**2d**	**14i**	66
25	4-$MeOCOC_6H_4$ (**g**)	**2d**	**14g**	55
26	*n*-$C_{11}H_{23}$ (**h**)	**2d**	**14h**	58

[a] The corresponding linear product, RCO*n*Bu, was obtained in 3–9% yield. [b] The product is volatile. DMF = *N*,*N*-dimethylformamide.

with conventional heating. Tricyclopentylphosphane proved to be the best ligand in the microwave-assisted reactions.

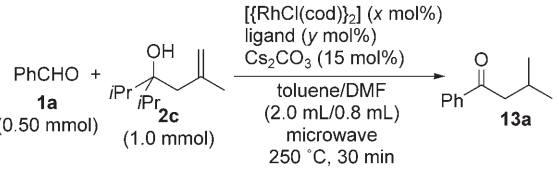
The higher reaction temperature led to poorer regioselectivity (Table 4, entries 1–8). In each case, a small amount of the corresponding linear product, equivalent to **10**, was detected. The linear products were not detected in the reactions in Table 2. The reactions with **2c** were facile (Table 4, entries 9–18). Cyclohexanecarbaldehyde (**1j**) reacted smoothly (Table 4, entry 17); however, the reaction of pivalaldehyde (**1k**) was sluggish (Table 4, entry 18). Allylation reactions with **2d** gave the desired products in good yield under the microwave-assisted conditions (Table 4, entries 19–26), although the equivalent reaction with conventional heating was not efficient [Eq. (1)]. Microwave heating at 250 °C may promote the retroallylation process, which is probably the rate-determining step. We were unsuccessful in our attempts to carry out a benzyl-transfer reaction with derivatives of 2-phenylethanol.

The attempted prenylation of benzaldehyde with **2e** under microwave irradiation again provided **15**, but in only 17% yield. Under these conditions, the isopropyl-substituted homoallylic alcohol **2f** proved to be a better reagent, with **15** formed in 33% yield [Eq. (2)]. We expect that the lower yields observed for **15** under the conditions of microwave irradiation result from an increase in side reactions during the transformation of **16** into **19**.



The effect of the ligand on the sequential methallylation–isomerization reaction is summarized in Table 5. The use of a trialkyl phosphine ligand rather than a triaryl phosphine generally led to a higher yield of the product. It was reported that (π-allyl)bis(triphenylphosphanyl)rhodium does not react with benzaldehyde at room temperature.[10] However, owing to the strong σ-donor character of trialkyl phosphines, π-allyl bis(trialkylphosphanyl)rhodium complexes appear to be nucleophilic enough to react with benzaldehyde. Tri-*tert*-butylphosphane is probably too bulky to promote the reaction (Table 5, entry 4). Bidentate ligands, such as binap, were not effective (Table 5, entries 6–8).

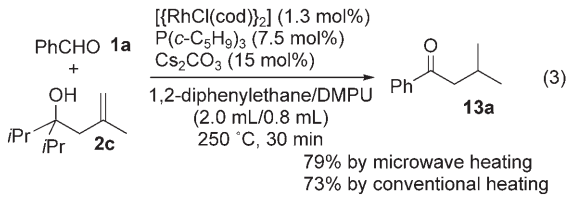
Table 5. Effect of ligand on the methallylation–isomerization reaction.



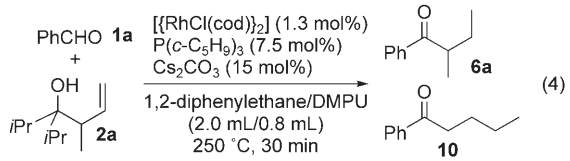
Entry	Ligand	*x*	*y*	Yield [%]
1	$P(c\text{-}C_5H_9)_3$	1.3	7.5	91
2	PMe_3	2.5	15	83
3	$P(c\text{-}C_6H_{11})_3$	2.5	15	72
4	$P(t\text{Bu})_3$	2.5	15	29
5	PPh_3	1.3	7.5	26
6	binap[a]	1.3	4	<1
7	dppe[b]	1.3	4	21
8	dppf[c]	1.3	4	9

[a] binap = 2,2′-bis(diphenylphosphanyl)-1,1′-binaphthyl. [b] dppe = 1,2-bis(diphenylphosphanyl)ethane. [c] dppf = 1,1′-bis(diphenylphosphanyl)-ferrocene.

Microwave heating is different from conventional external heating in principle and can have so-called nonthermal microwave effects.[11] We investigated whether such effects were in operation [Eq. (3)]. The reaction of **1a** with **2c** was complete within 30 min in the solvent mixture 1,2-diphenylethane (b.p.: 284 °C)/*N*,*N*′-dimethylpropylene urea (DMPU; b.p.: 146 °C at 44 mmHg) at 250 °C when the reaction mixture was heated by microwave irradiation or in a sand bath. No significant differences were observed.



Under the microwave-assisted conditions at 250 °C, the reactions with **2a** were not regioselective (Table 4, entries 1–8). To investigate whether the lower regioselectivity was due to a nonthermal microwave effect or to the high temperature, we treated benzaldehyde with **2a** in the presence of the same catalyst system at 250 °C with conventional heating and under microwave irradiation [Eq. (4)]. The regioselectivity of the two reactions was similar. Thus, the lower regioselectivity appears to be due to the high temperature.



Conclusions

We have developed an allyl-transfer reaction of homoallylic alcohols with aldehydes through a retroallylation reaction as a carbon–carbon bond-cleaving process with the aid of a rhodium catalyst. Microwave heating at 250 °C accelerates the reaction, which can be viewed as an alternative to the

commonly used alkylation–oxidation sequence for the conversion of aldehydes into ketones.

Experimental Section

General

All microwave-assisted reactions were carried out with a focused microwave unit (Biotage Initiator) with a maximum irradiation power of 400 W. Each reaction was run in a 5-mL glass pressure vial, which is a commercially available special vial for the Biotage Initiator. After the indicated temperature was reached (it took 6 min to reach 250 °C), controlled microwave irradiation was started and was continued for 30 min, during which the temperature of the reaction mixture was kept constant. For classical heating at 250 °C (for the reaction in Equation (3)), glassware containing the reaction mixture was heated in a sand bath.

^{1}H (500 MHz) and ^{13}C NMR (125.7 MHz) spectra were recorded on a Varian Unity Inova 500 spectrometer in $CDCl_3$. Chemical shifts (δ) are given in parts per million relative to the tetramethylsilane signal at 0.00 ppm (^{1}H) and relative to the $CDCl_3$ signal at 77.0 ppm (^{13}C). ^{19}F NMR spectra were recorded in $CDCl_3$ with fluorotrichloromethane as an external standard. IR spectra were recorded on a Shimadzu FTIR-8200PC spectrometer. Mass spectra were recorded on a JEOL Mstation 700 spectrometer. TLC analysis was performed on commercial glass plates with a 0.25-mm layer of Merck silica gel 60F_{254}. Silica gel (Wakogel 200 mesh) was used for column chromatography. Elemental analysis was carried out at the Elemental Analysis Center of Kyoto University.

Unless otherwise noted, materials obtained from commercial suppliers were used without further purification. Xylene and dioxane were dried over slices of sodium. Chloro(1,5-cyclooctadiene)rhodium dimer and PMe_3 (as a 1.0 M solution in toluene) were purchased from Aldrich. P(tBu)$_3$ and P(c-C_5H_9)$_3$ were obtained from Wako Pure Chemicals and TCI, respectively, and were diluted to 1.0 M in hexane. The solutions of the ligands were stored strictly under argon. Cesium carbonate was purchased from Wako Pure Chemicals. The homoallylic alcohols **2** were prepared by conventional methods, except for **2b**.[2p]

Syntheses

Typical procedure for the crotylation of aromatic aldehydes: [{RhCl(cod)}$_2$] (6 mg, 0.0125 mmol) and Cs_2CO_3 (24 mg, 0.075 mmol) were placed in a reaction flask. Dioxane (3.0 mL) and PMe_3 (1.0 M in toluene, 0.05 mL, 0.05 mmol) were added dropwise, and the resulting suspension was stirred for 10 min at room temperature. A solution of **2a** (170 mg, 1.0 mmol) in dioxane (2.0 mL) and **1a** (53 mg, 0.5 mmol) were then added, and the mixture was heated at reflux for 8 h. The reaction was then quenched with water (10 mL). Extraction and purification provided 2-methyl-1-phenyl-3-buten-1-ol (**6a**; 48 mg, 0.29 mmol, 58%; *erythro*/*threo* = 49:51).

Typical procedure for the sequential methallylation–isomerization of aldehydes: [{RhCl(cod)}$_2$] (6 mg, 0.0125 mmol) and Cs_2CO_3 (24 mg, 0.075 mmol) were placed in a reaction flask. Xylene (3.0 mL) and P(tBu)$_3$ (1.0 M in hexane, 0.05 mL, 0.05 mmol) were added dropwise, and the resulting suspension was stirred for 10 min at room temperature. A solution of **2c** (170 mg, 1.0 mmol) in xylene (2.0 mL) and **1d** (69 mg, 0.5 mmol) were then added, and the mixture was heated at reflux for 24 h then poured into water (10 mL). Extraction with hexane/ethyl acetate (5:1) followed by purification by silica-gel column chromatography afforded 3-methyl-1-(4-methoxyphenyl)-1-butanone (**13d**; 75 mg, 0.39 mmol, 77% yield).

Typical procedure for the microwave-assisted reaction: Cesium carbonate (24 mg, 0.075 mmol) and [{RhCl(cod)}$_2$] (3 mg, 0.006 mmol) were placed in a 5-mL glass pressure vial. The vial was flushed with argon and sealed with a polytetrafluoroethylene–silicone septum. Toluene (0.5 mL) and tricyclopentylphosphane (1.0 M in hexane, 0.038 mL, 0.038 mmol) were added, and the suspension was stirred for 10 min at room temperature. A solution of **2c** (170 mg, 1.0 mmol) in toluene (1.5 mL), benzaldehyde (**1a**, 53 mg, 0.50 mmol), and DMF (0.80 mL) were added, and the resulting mixture was heated at 250 °C with stirring for 30 min in the microwave reactor. The mixture was then cooled to room temperature, and the reaction was quenched with water (3 mL). Extraction with hexane/ethyl acetate (10:1) followed by purification by silica-gel column chromatography afforded 3-methyl-1-phenyl-1-butanone (**13a**; 74 mg, 0.45 mmol, 91%).

The spectra of compounds **1f**,[12] **1i**,[13] **2a–e**,[14] **3a**,[15] **3b**,[16] **3c**,[17] **3d**,[18] **3e**,[18] **3g**,[18] **6a**,[19] **6b**,[20] **6d**,[14] **6e**,[14] **13a**,[19] **13b**,[20] **13d**,[21] **13e**,[22] **13i**,[23] **13j**,[24] and **14c**[25] were identical to those reported in the literature.

2f: 3-Isopropyl-2,4,4-trimethyl-5-hexen-3-ol: IR (neat): $\tilde{\nu}$ = 3569, 3082, 1632, 1477, 1383, 1281, 1121, 989 cm^{-1}; ^{1}H NMR ($CDCl_3$): δ = 1.08 (d, J = 7.0 Hz, 6H), 1.12 (d, J = 7.0 Hz, 6H), 1.17 (s, 6H), 2.16 (sept, J = 7.0 Hz, 2H), 4.99 (dd, J = 11.0, 1.5 Hz, 1H), 5.01 (dd, J = 17.5, 1.5 Hz, 1H), 6.22 ppm (dd, J = 17.5, 11.0 Hz, 1H); the signal for the OH hydrogen atom was not observed; ^{13}C NMR ($CDCl_3$): δ = 20.7, 21.1, 24.7, 35.6, 47.3, 79.5, 111.7, 148.0 ppm; elemental analysis: calcd (%) for $C_{12}H_{24}O$: C 78.20, H 13.12; found: C 78.33, H 13.38.

3f: 4-(1-Hydroxy-2-methyl-3-butenyl)phenyl phenyl ketone (mixture of *erythro* and *threo* isomers): IR (neat): $\tilde{\nu}$ = 3446, 2973, 2874, 1645, 1599, 1579, 1448, 1413, 1280, 1178, 1150, 1100, 1001, 924, 844, 749, 702 cm^{-1}; ^{1}H NMR (*erythro* isomer, $CDCl_3$): δ = 1.02 (d, J = 7.0 Hz, 3H), 2.06 (d, J = 3.5 Hz, 1H), 2.65 (sept, J = 7.0 Hz, 1H), 4.76 (t, J = 3.5 Hz, 1H), 5.10–5.15 (m, 2H), 5.77–5.85 (m, 1H), 7.44–7.47 (m, 2H), 7.48–7.52 (m, 2H), 7.61 (tt, J = 7.0, 1.0 Hz, 1H), 7.80–7.82 ppm (m, 4H); ^{1}H NMR (*threo* isomer, $CDCl_3$): δ = 0.95 (d, J = 7.0 Hz, 3H), 2.28 (d, J = 2.5 Hz, 1H), 2.53 (sept, J = 7.0 Hz, 1H), 4.48 (dd, J = 7.0, 2.5 Hz, 1H), 5.23–5.26 (m, 2H), 5.77–5.85 (m, 1H), 7.44–7.57 (m, 2H), 7.48–7.52 (m, 2H), 7.61 (tt, J = 7.0, 1.0 Hz, 1H), 7.80–7.82 ppm (m, 4H); ^{13}C NMR (mixture of isomers, $CDCl_3$): δ = 13.5, 14.1, 16.4, 22.7, 31.0, 31.6, 44.6, 46.4, 76.6, 77.3, 116.2, 117.6, 126.3, 126.7, 128.3, 130.0, 130.0, 130.0, 130.1, 130.3, 132.4, 132.4, 136.5, 136.9, 137.6, 137.7, 139.8, 139.9, 147.1, 147.2, 196.5 ppm; elemental analysis: calcd (%) for $C_{18}H_{18}O_2$: C 81.17, H 6.81; found: C 81.45, H 6.88.

6c: 1-(4-Trifluoromethylphenyl)-2-methyl-1-butanone: IR (neat): $\tilde{\nu}$ = 2971, 2937, 2880, 1692, 1463, 1410, 1326, 1268, 1217, 1170, 1132, 1114, 1068, 1017, 974, 857, 592 cm^{-1}; ^{1}H NMR ($CDCl_3$): δ = 0.94 (t, J = 7.5 Hz, 3H), 1.22 (d, J = 7.0 Hz, 3H), 1.48–1.56 (m, 1H), 1.81–1.89 (m, 1H), 3.37–3.44 (m, 1H), 7.75 (d, J = 8.0 Hz, 2H), 8.06 ppm (d, J = 8.0 Hz, 2H); ^{13}C NMR ($CDCl_3$): δ = 11.7, 16.5, 26.5, 42.5, 123.6 (q, J = 272.5 Hz), 125.7 (q, J = 3.8 Hz), 128.5, 134.1 (q, J = 32.7 Hz), 139.5, 203.4 ppm; ^{19}F NMR ($CDCl_3$): δ = −63.7 ppm; elemental analysis: calcd (%) for $C_{12}H_{13}F_3O$: C 62.60, H 5.69; found: C 62.36, H 5.39.

6g: Methyl 4-(2-methyl-1-oxobutyl)benzoate: IR (neat): $\tilde{\nu}$ = 2936, 2877, 1729, 1683, 1572, 1504, 1436, 1407, 1373, 1280, 1215, 1182, 1109, 1006, 956, 870, 826, 788, 722 cm^{-1}; ^{1}H NMR ($CDCl_3$): δ = 0.93 (t, J = 7.5 Hz, 3H), 1.21 (d, J = 7.0 Hz, 3H), 1.47–1.55 (m, 1H), 1.80–1.88 (m, 1H), 3.41 (sept, J = 7.0 Hz, 1H), 3.96 (s, 3H), 8.00 (dt, J = 8.5, 2.0 Hz, 2H), 8.13 ppm (dt, J = 8.5, 2.0 Hz, 2H); ^{13}C NMR ($CDCl_3$): δ = 11.7, 16.5, 26.5, 42.5, 52.4, 128.1, 129.8, 133.6, 140.1, 166.3, 204.0 ppm; elemental analysis: calcd (%) for $C_{13}H_{16}O_3$: C 70.89, H 7.32; found: C 70.77, H 7.25.

6i: 1-[4-(4-Methylbenzoyl)phenyl]-2-methyl-1-butanone: IR (neat): $\tilde{\nu}$ = 2966, 2937, 2876, 1683, 1659, 1404, 1279, 930 cm^{-1}; ^{1}H NMR ($CDCl_3$): δ = 0.94 (t, J = 7.0 Hz, 3H), 1.22 (d, J = 6.5 Hz, 3H), 1.82–1.91 (m, 1H), 2.45 (s, 3H), 3.40–3.47 (m, 2H), 7.30 (dd, J = 8.5, 1.0 Hz, 2H), 7.72–7.74 (dm, J = 8.0 Hz, 2H), 7.84–7.86 (dm, J = 8.5 Hz, 2H) 8.03–8.05 ppm (dm, J = 8.0 Hz, 2H); ^{13}C NMR ($CDCl_3$): δ = 12.0, 16.8, 21.9, 26.8, 42.8, 128.3, 129.4, 130.2, 130.6, 134.5, 139.5, 141.7, 144.1, 195.9. 204.2 ppm; elemental analysis: calcd (%) for $C_{19}H_{20}O_2$: C 81.40, H 7.19; found: C 81.15, H 7.19.

13c: 1-(4-Trifluoromethylphenyl)-3-methyl-1-butanone: IR (neat): $\tilde{\nu}$ = 2958, 1684, 1662, 1598, 1448, 1404, 1367, 1277, 1211, 938, 926, 743, 718, 699, 655 cm^{-1}; ^{1}H NMR ($CDCl_3$): δ = 1.02 (d, J = 7.0 Hz, 6H), 2.27–2.35 (m, 1H), 2.87 (d, J = 7.0 Hz, 2H), 7.74 (d, J = 8.0 Hz, 2H), 8.06 ppm (d, J = 8.0 Hz, 2H); ^{13}C NMR ($CDCl_3$): δ = 22.7, 25.0, 47.7, 125.6 (q, J = 3.65 Hz, 1C), 128.4, 130.2, 134.0, 139.9, 199.2 ppm; ^{19}F NMR ($CDCl_3$): δ = −63.7; elemental analysis: calcd (%) for $C_{12}H_{13}F_3O$: C 62.60, H 5.69; found: C 62.85, H 5.61.

13f: 1-(4-Benzoylphenyl)-3-methyl-1-butanone: IR (neat): $\tilde{\nu}$ = 2958, 1684, 1662, 1598, 1448, 1404, 1367, 1277, 1211, 938, 926, 743, 718, 699, 655 cm^{-1}; ^{1}H NMR ($CDCl_3$): δ = 1.03 (d, J = 6.5 Hz, 6H), 2.29–2.38 (m, 1H), 2.90

(d, J=6.5 Hz, 2H), 7.52 (tt, J=7.5, 1.5 Hz, 2H), 7.64 (tt, J=7.5, 1.5 Hz, 1H), 7.82 (dt, J=8.0, 1.5 Hz, 2H), 7.87 (dt, J=8.0, 1.5 Hz, 2H), 8.06 (dt, J=8.0, 1.5 Hz, 2H); ^{13}C NMR ($CDCl_3$): δ=22.7, 25.1, 47.8, 127.9, 128.5, 130.0, 130.1, 133.0, 136.9, 139.9, 141.1, 196.0, 199.7 ppm; elemental analysis: calcd (%) for $C_{18}H_{18}O_2$: C 81.17, H 6.81; found: C 81.05, H 6.84.

13g: Methyl 4-(3-methyl-1-oxobutyl)benzoate: IR (neat): $\tilde{\nu}$=3674, 2956, 1722, 1683, 1504, 1436, 1407, 1365, 1279, 1198, 1109, 763, 695 cm^{-1}; ^{1}H NMR ($CDCl_3$): δ=1.01 (d, J=6.5 Hz, 6H), 2.27–2.35 (m, 1H), 2.88 (d, J=7.0 Hz, 2H), 3.96 (s, 3H), 8.01 (d, J=8.5 Hz, 2H), 8.13 ppm (d, J=8.5 Hz, 2H); ^{13}C NMR ($CDCl_3$): δ=22.7, 25.0, 47.8, 52.5, 128.0, 129.8, 133.6, 140.5, 166.3, 199.7 ppm; elemental analysis: calcd (%) for $C_{13}H_{16}O_3$: C 70.89, H 7.32; found: C 71.00, H 7.53.

13h: 2-Methyl-4-pentadecanone: IR (neat): $\tilde{\nu}$=2927, 2855, 1717, 1468, 1410, 1367, 1287, 1144, 1040, 721 cm^{-1}; ^{1}H NMR ($CDCl_3$): δ=0.89 (t, J=7.0 Hz, 3H), 0.92 (d, J=6.5 Hz, 6H), 1.26–1.31 (m, 16H), 1.55–1.59 (m, 2H), 2.15 (sept, J=6.5 Hz, 1H), 2.28 (d, J=7.5 Hz, 2H), 2.37 ppm (t, J=7.5 Hz, 2H); ^{13}C NMR ($CDCl_3$): δ=14.1, 18.2, 22.6, 22.7, 23.8, 24.6, 29.3, 29.3, 29.4, 29.5, 29.6, 31.9, 43.4, 51.8, 211.4 ppm; elemental analysis: calcd (%) for $C_{16}H_{32}O$: C 79.93, H 13.41; found: C 79.96, H 13.52.

13i: 1-[4-(4-Methylbenzoyl)phenyl]-3-methyl-1-butanone: M.p.: 63 °C; IR (nujol): $\tilde{\nu}$=2966, 2933, 2876, 1684, 1659, 1607, 1278, 930 cm^{-1}; ^{1}H NMR ($CDCl_3$): δ=1.02 (d, J=6.5 Hz, 6H), 2.32 (tsept, J=7.0, 6.5 Hz, 1H), 2.45 (s, 3H), 2.88 (d, J=7.0 Hz, 2H), 7.30 (d, J=8.0 Hz, 2H), 7.72 (d, J=8.0 Hz, 2H), 7.83 (d, J=8.5 Hz, 2H), 8.03 (d, J=8.5 Hz, 2H); ^{13}C NMR ($CDCl_3$): δ=21.7, 22.7, 25.1, 47.8, 127.9, 129.2, 129.9, 130.3, 134.3, 139.7, 141.5, 143.9, 195.7, 199.7 ppm; elemental analysis: calcd (%) for $C_{19}H_{20}O_3$: C 81.40, H 7.19; found: C 81.24, H 7.31.

14g: Methyl 4-(1-oxobutyl)benzoate: M.p.: 84 °C; IR (nujol): $\tilde{\nu}$=2924, 2854, 1722, 1675, 1456, 1285, 1112, 745 cm^{-1}; ^{1}H NMR ($CDCl_3$): δ=1.01 (t, J=7.5 Hz, 3H), 1.78 (tq, J=7.5, 7.0 Hz, 2H), 2.97 (t, J=7.0 Hz, 2H), 3.98 (s, 3H), 8.00 (dt, J=8.5, 2.0 Hz, 2H), 8.11 ppm (dt, J=8.5, 2.0 Hz, 2H); ^{13}C NMR ($CDCl_3$): δ=14.1, 17.8, 41.1, 52.7, 128.2, 130.1, 133.9, 140.6, 166.5, 200.1 ppm; elemental analysis: calcd (%) for $C_{12}H_{14}O_3$: C 69.89, H 6.84; found: C 69.64, H 6.80.

14i: 1-[4-(4-Methylbenzoyl)phenyl]-1-butanone: M.p.: 66 °C; IR (nujol): $\tilde{\nu}$=2966, 2933, 2876, 1684, 1659, 1607, 1313, 1278, 1216, 930 cm^{-1}; ^{1}H NMR ($CDCl_3$): δ=1.03 (t, J=7.5 Hz, 3H), 1.80 (tq, J=7.5, 7.5 Hz, 2H), 2.43 (s, 3H), 3.00 (t, J=7.5 Hz, 2H), 7.29 (d, J=8.0 Hz, 2H), 7.71 (d, J=8.0 Hz, 2H), 7.84 (d, J=8.0 Hz, 2H), 8.05 ppm (d, J=8.0 Hz, 2H); ^{13}C NMR ($CDCl_3$): δ=13.8, 17.6, 21.7, 40.9, 127.8, 129.2, 129.9, 130.3, 134.3, 139.4, 141.5, 143.9, 195.7, 199.9 ppm; elemental analysis: calcd (%) for $C_{18}H_{18}O_2$: C 81.18, H 6.91; found: C 81.17, H 6.81.

15: 2,3-Dimethyl-1-phenyl-1-butanone: IR (neat): $\tilde{\nu}$=2963, 2934, 2875, 1683, 1448, 1217, 969 cm^{-1}; ^{1}H NMR ($CDCl_3$): δ=0.89 (d, J=7.0 Hz, 3H), 0.94 (d, J=7.0 Hz, 3H), 1.13 (d, J=7.0 Hz, 3H), 2.09 (dsept, J=7.0, 7.0 Hz, 1H), 3.28 (dq, J=7.0, 7.0 Hz, 1H), 7.44–7.47 (m, 2H), 7.53–7.56 (m, 1H), 7.93–7.95 ppm (m, 2H); ^{13}C NMR ($CDCl_3$): δ=13.6, 18.9, 21.8, 30.9, 47.1, 128.4, 128.8, 133.0, 137.6, 205.1 ppm; elemental analysis: calcd (%) for $C_{12}H_{16}O$: C 81.77, H 9.15; found: C 81.89, H 9.17.

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