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[RuCl$_2$(*p*-cymene)]$_2$-Catalyzed Conjugate Addition of Arylboronic Acids to α,β-Unsaturated Ketones under Ligand-Free and Neutral Conditions

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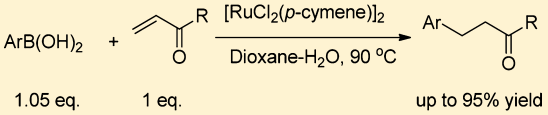
Supporting Information

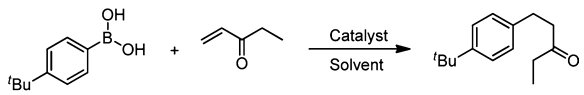
ABSTRACT: A simple and efficient Ru-catalyzed conjugate addition reaction of arylboronic acids to α,β-unsaturated ketones under neutral conditions without any additional ligands has been developed. This Ru(II)-catalytic system both fulfilled the inhibition of the β-hydride elimination in the catalytic cycle and minimized the protonolysis of arylboronic acids.



During the past decades, the transition-metal-catalyzed 1,4-conjugate addition reaction of organometallic reagents to α,β-unsaturated carbonyl compounds has emerged as a powerful tool for the construction of carbon−carbon bonds.[1] Among various organometallic reagents, organoboron reagents were widely used due to their readily availability, stability, and low toxicity.[2] Rh(I)-catalyzed conjugate addition of arylboron reagents to α,β-unsaturated carbonyl compounds has been well-documented[3] since the pioneering work of Miyaura and co-workers.[4] Recently, the enantioselective conjugate addition using chiral dienes and olefin-heteroatom ligands were extensively studied.[5] More recently, the conjugate addition was also catalyzed by Pd,[6] Ni,[7] and Pt[8] complexes. Although Ru-catalyzed addition reactions of arylboronic acids to aldehydes and ketones have been reported since 2009,[9] Ru-catalyzed conjugate addition has been rarely explored. One exception is the work by Hayashi et al,[10] in which the combination of [RuCl$_2$(*p*-cymene)]$_2$ and P(*t*-Bu)$_2$(2-PhC$_6$H$_4$) catalyzed the reaction of arylboronic acids with linear β-substituted enones under basic conditions to give Michael addition-type and Heck-type products. In 2011 Kochi and Kakiuchi reported a Ru-catalyzed cross-coupling of organoboron reagents with 2- and 4-(2-methoxyethyl)pyridines, the reaction proceeding via a kind of addition of organoboron reagents with vinylpyridine intermediates formed by dehydromethoxylation.[11] Up to now, there have been no examples for the Ru-catalyzed selective conjugate addition of arylboronic acids to vinyl ketones to produce 1,4-addition products.[12]

In the transition-metal-catalyzed addition reaction of arylboronic acids with α,β-unsaturated carbonyl compounds, in order to facilitate the transmetalation of the catalyst precursor [MX] with boronic acids, a base was often employed to form the active catalyst [MOH]. However, the base was usually unnecessary if [MOR] (OR = OH, OAc, acac, etc.) was used as catalyst precursor.[13] We initiated our studies by investigating the reaction of pent-1-en-3-one (**2a**) with (4-(*tert*-butyl)phenyl)boronic acid (**1a**) in the presence of [RuCl$_2$(*p*-cymene)]$_2$ (2.0 mol %) and PPh$_3$ (5.0 mol %) as the catalyst in dioxane/H$_2$O (v/v = 100:1). As illustrated in Table 1, in the presence of 1 equiv of KOH (10 M aqueous), the reaction gave the desired product in only 21% yield, accompanied by Heck-type product (14%) and a large amount of *tert*-butylbenzene resulted from the protonolysis of (4-(*tert*-butyl)phenyl)boronic

Table 1. Ru-Catalyzed 1,4-Addition of 1a to 2a[a]



1a **2a** **3aa**

entry	catalyst	base[c]	solvent[b]	yield (%)
1	[RuCl$_2$(*p*-cymene)]$_2$ + PPh$_3$	KOH	dioxane/H$_2$O	21
2	[RuCl$_2$(*p*-cymene)]$_2$ + PPh$_3$	K$_2$CO$_3$	dioxane/H$_2$O	17
3	[RuCl$_2$(*p*-cymene)]$_2$ + PPh$_3$	NO	dioxane/H$_2$O	91
4	[RuCl$_2$(*p*-cymene)]$_2$	NO	dioxane/H$_2$O	95
5	[RuCl$_2$(*p*-cymene)]$_2$	NO	THF/H$_2$O	92
6	[RuCl$_2$(*p*-cymene)]$_2$	NO	toluene/H$_2$O	88
7	[RuCl$_2$(*p*-cymene)]$_2$	NO	DCE/H$_2$O	92
8	[RuCl$_2$(*p*-cymene)]$_2$	NO	acetone/H$_2$O	93
9	[Ru(benzene)Cl$_2$]$_2$	NO	dioxane/H$_2$O	92
10	RuCl$_2$(PPh$_3$)$_3$	NO	dioxane/H$_2$O	20
11	[RuCl$_2$(COD)]$_n$	NO	dioxane/H$_2$O	ND
12	RuCl$_3$·xH$_2$O	NO	dioxane/H$_2$O	ND
13	[RuCl$_2$(*p*-cymene)]$_2$	NO	dioxane/H$_2$O	89[d]
14	[RuCl$_2$(*p*-cymene)]$_2$	NO	dioxane/H$_2$O	93[e]

[a]All reactions were carried out with **1** (0.5 mmol), **2** (0.5 mmol), and ruthenium complex (2.0 mol %) in a solvent (3 mL) at 90 °C under N$_2$ for 10 h. Yield determined by GC with durene as an internal standard. [b]v/v = 100:1. [c]Base, 0.5 mmol; PPh$_3$, 0.025 mmol. [d]Reaction at 50 °C. [e]Reaction at 120 °C.

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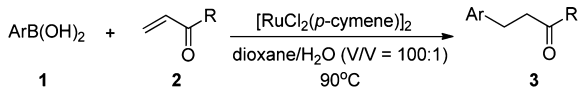
acid. The weaker base K_2CO_3 did not improve the reaction (Table 1, entries 1, 2). This result is similar to those reported earlier by Hayashi.[10] It was surprising to find that when the reaction was carried out in the absence of a base, the conjugate addition proceeded smoothly, together with a thimbleful of *tert*-butylbenzene and no Heck-type product (Table 1, entry 3). When the reaction is carried out under the acidic conditions, *tert*-butylbenzene will be the major product. Other organoboron reagents such as Ph_4BNa and 5,5-dimethyl-2-phenyl-1,3,2-dioxaborinane were inefficient, no product was observed when Ph_4BNa was used, and the conversion was very low for 5,5-dimethyl-2-phenyl-1,3,2-dioxaborinane. Replacing the catalyst with $RuCl_2(PPh_3)_3$, the reaction gave **3aa** in only 20% yield (Table 1, entry 10); $[Ru(benzene)Cl_2]_2$ as catalyst gave comparable yields (Table 1, entries 4 vs 9).

Even better yield of the product was obtained when the reaction was conducted in the absence of PPh_3, implying that PPh_3 was not necessary for this reaction. Other solvents such as THF, DCE, toluene, and acetone were all acceptable solvents in our catalytic system (Table 1, entries 4–8). Other ruthenium catalysts are inefficient, and $[Ru(COD)Cl_2]_n$ and $RuCl_3{\cdot}xH_2O$ are totally inert (Table 1, entries 11, 12). This reaction was insensitive to the temperature. When the reaction was carried out at 50 °C, the yield was slightly decreased, along with more *tert*-butylbenzene being produced; when the reaction was carried out at 120 °C, the yield was almost equal to that at 90 °C.

To investigate the substrate scope, we explored other arylboronic acids as nucleophiles for this reaction. The reaction tolerated various functional groups, such as OCF_3, Cl, CF_3, and OCH_3 at the *para* and/or *meta* position of the phenyl ring of arylboronic acids **1** (Table 2, entries 1–10). These results indicated that the reaction was not sensitive to the electronic properties of the substituents. Arylboronic acids **1a–l** can efficiently react with **2a** to afford the corresponding addition products in excellent yields (Table 2, entries 1–13), albeit vulnerable to the position of the substituent at the *ortho* position of the phenyl rings. For example, 2-methylphenylboronic acid (**1b**) and naphthalen-1-ylboronic acid (**1f**) gave **3ba** and **3fa** in only 64% and 34% yield, respectively (Table 2, entries 2, 6), with a large amount of arylboronic acids being protonolyzed. To our delight, the yields were increased to 92% and 94%, respectively, when 2.5 equiv of **1b** and **1f** was used. Other vinyl ketones, such as 1-(*p*-tolyl)prop-2-en-1-one (**2b**) and 5-phenylpent-1-en-3-one (**2c**), are acceptable reactants. However, **2b** reacted with **1a** to give **3ab** in 68% yield, because **2b** polymerized easily during the reaction. This problem can be solved by adding a polymerization inhibitor. As a result, the yield was increased to 92% when 2,6-di-*tert*-butylphenol (5 mol % relative to **2b**) was added. It is worth noting that butyl acrylate (**2d**), a difficult substrate for transition-metal-catalyzed 1,4-addition reaction, worked fairly well. When **2d** reacted with **1a**, product **3ad** was obtained in 75% yield accompanied by 20% of Heck-type product.

Furthermore, the reaction is very sensitive to the steric hindrance of the alkenes **2**. When cyclopentenone (**2e**) was used as substrate, **3ae** was obtained in only 41% yield; by increasing 4-*tert*-butylphenylboronic acid loading from 1.05 equiv to 2.5 equiv relative to **2e**, up to 77% yield was obtained (Table 2, entry 16). Other more sterically hindered α,β-unsaturated ketones, either cyclic or linear, such as cyclohex-2-enone and benzalacetone, are not suitable substrates for this reaction (Table 2, entries 17 and 18). This is complementary to

Table 2. Ru-Catalyzed 1,4-Addition of 1a to 2aa[a]



1 2 3

2a: R = Et
2b: R = *p*-MeC$_6$H$_4$
2c: R = (CH$_2$)$_2$Ph
2d: R = OBu
2e: cyclopent-2-enone
2f: cyclohex-2-enone
2g: (E)-4-phenylbut-3-en-2-one

entry	Ar	2	product	yield (%)
1	*p*-Bu^{t}C$_6$H$_4$ (**1a**)	**2a**	**3aa**	95 (91[b])
2	*o*-MeC$_6$H$_4$ (**1b**)	**2a**	**3ba**	64 (92[c])
3	*m*-MeC$_6$H$_4$ (**1c**)	**2a**	**3ca**	93
4	*p*-MeC$_6$H$_4$ (**1d**)	**2a**	**3da**	92
5	*p*-MeOC$_6$H$_4$ (**1e**)	**2a**	**3ea**	90
6	1-naphthyl (**1f**)	**2a**	**3fa**	34 (94[c])
7	*p*-CF$_3$C$_6$H$_4$ (**1g**)	**2a**	**3ga**	90
8	*p*-ClC$_6$H$_4$ (**1h**)	**2a**	**3ha**	92
9	*p*-CF$_3$OC$_6$H$_4$ (**1i**)	**2a**	**3ia**	94
10	1,3-benzodioxol-5-yl (**1j**)	**2a**	**3ja**	94
11	C$_6$H$_5$ (**1k**)	**2a**	**3ka**	89
12	styryl (**1l**)	**2a**	**3la**	57[d]
13	**1a**	**2b**	**3ab**	68 (92[e])
14	**1a**	**2c**	**3ac**	92
15	**1a**	**2d**	**3ad**	75[f]
16	**1a**	**2e**	**3ae**	41 (77[c])
17	**1a**	**2f**	**3af**	trace[c]
18	**1a**	**2g**	**3ag**	trace[c]

[a]All reactions were carried out with **1** (1.05 mmol), **2** (1.0 mmol), and $[RuCl_2(p\text{-cymene})]_2$ (2.0 mol %) in 3 mL of dioxane/H_2O (3 mL, v/v = 100:1) at 90 °C under N_2 for 10 h. [b]Reaction run at 50 mmol scale. [c]Reactions were carried out at 120 °C with 2.5 equiv of arylboronic acid. [d]With 10% Heck-type product. [e]2,6-Di-*tert*-butyl phenol (0.05 mmol) was added. [f]With 20% Heck-type product.

both Hayashi's work, in which vinyl ketones did not work with $[RuCl_2(p\text{-cymene})]_2$ and P(*t*-Bu)$_2$(2-PhC$_6$H$_4$) as catalyst under basic conditions,[10] and Lu's work, where in a palladium-catalyzed conjugate reaction of aryl boronic acids with α,β-unsaturated carbonyl compounds only sterically hindered α,β-unsaturated ketones work efficiently.[14]

To understand the reaction and to explain the different reactivity of α,β-unsaturated carbonyl compounds, a mechanism was proposed according to the literature (Scheme 1).[13] Transmetalation between $[RuCl_2(p\text{-cymene})]_2$ and arylboronic acid generates intermediate **A**. Insertion of the C–C double bond of α,β-unsaturated ketones into the Ru–C bond of **A** affords the intermediate **C**, which may undergo β-hydride elimination to give product **D** or be in equilibrium with intermediate **E**, which protonolyzes to give the product **3** and regenerates the catalyst.

Once intermediate **A** is formed, the central metal will coordinate with cymene and bind with an aromatic ring and a halogen. Because of the bulkiness of the catalyst, it is difficult for a bulky enone to coordinate to ruthenium, accounting for the highly steric demanding of the reactants. Once the coordination of enone and subsequent insertion of the C–C double bond of enone into the Ru–C bond occurs, quick enolization takes place to afford intermediate **E**, which upon hydrolysis gives the 1,4-addition product and regenerates the catalyst.

As for butyl acrylate, after the insertion of the C=C bond of butyl acrylate into the Ru–C bond, intermediate **C** does not form O-bound enolate intermediate **E** easily and completely.[15]

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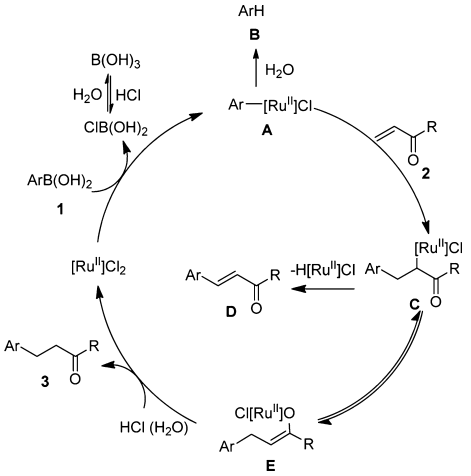
Scheme 1. Proposed Mechanism for $[RuCl_2(p\text{-cymene})]_2$-Catalyzed 1,4-Addition Reaction[a]



[a]Ligands cymene, benzene were omitted for clarity.

Therefore, part of intermediate **C** degrades to compound **D** via β-hydride elimination.

In summary, we have developed the first simple and efficient Ru-catalyzed conjugate addition reaction of arylboronic acids to enones under neutral conditions without any additional ligands. Comparing to other transition-metal-catalyzed conjugate addition reaction conditions, this Ru(II)-catalyzed system efficiently inhibited the β-hydride elimination and protonolysis of arylboronic acids.

EXPERIMENTAL SECTION

General. Commercially available reagents were used throughout without further purification other than those detailed below. The solvents were pretreated by the following procedures: tetrahedronfuran, toluene, and dioxane were distilled over sodium benzopheneone ketyl under nitrogen. 1,2-Dichloroethane was distilled over calcium hydride. Acetone was distilled over calcium sulfate anhydrous under nitrogen. All reactions were carried out under an atmosphere of nitrogen using standard Schlenk techniques or in a nitrogen-filled glovebox, unless otherwise noted. ^{1}H NMR spectra were recorded at 400 MHz, with TMS as internal standard. ^{13}C NMR spectra were obtained at 100 MHz and referenced to the central peak of 77.0 ppm for $CDCl_3$. Coupling constants (J) are reported in hertz and refer to apparent peak multiplications. Flash column chromatography was performed on silica gel (300−400 mesh).

Procedures for the Preparation of 2b and 2c. A solution of *N*-methoxy-*N*,4-dimethylbenzamide (895.0 mg, 5.0 mmol) in THF (30.0 mL) was cooled to −78 °C. Vinyl magnesium bromide (1 M solution in THF, 5.5 mL, 5.5 mmol) was slowly added, and the mixture was stirred at −78 °C for 10 min. Then the mixture was stirred for a further 5 h at −50 °C, and the reaction was quenched with saturated aqueous NH_4Cl (10 mL). After the removal of the organic solvent and extraction with ethyl acetate (2 × 20 mL), the combined organic phase was washed with brine (30 mL), then dried over $MgSO_4$, and concentrated in vacuo. The product was purified by silica gel chromatography (PE/EA = 50:1) to give **2b** (452 mg, 62%) as a colorless liquid. Similarly, **2c** (481 mg, 5 mmol scale) was synthesized in 60% yield.

1-(*p*-Tolyl)prop-2-en-1-one (2b).[16] Colorless liquid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.85 (d, J = 8.4 Hz, 2H), 7.25 (d, J = 8.0 Hz, 2H), 7.15 (dd, J = 17.2, 10.4 Hz, 1H), 6.42 (dd, J = 17.2, 1.6 Hz, 1H), 5.87 (dd, J = 10.4, 1.6 Hz, 1H), 2.39 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 190.6, 144.1, 134.9, 132.5, 129.9, 129.5, 129.0, 21.9.

5-Phenylpent-1-en-3-one (2c).[17] Colorless liquid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.32−7.27 (m, 2H), 7.22−7.18 (m, 3H), 6.36 (dd, J = 17.6, 10.4 Hz, 1H), 6.22 (dd, J = 17.6, 1.2 Hz, 1H), 5.84 (dd, J = 10.4, 1.2 Hz, 1H), 2.99−2.90 (m, 4H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 199.8, 141.4, 136.7, 128.8, 128.7, 128.5, 126.4, 41.4, 30.0.

Typical Procedure for the Conjugate Addition of Arylboronic Acids to Pent-1-en-3-one. To a Schlenk tube under N_2 were added arylboronic acid (1.05 mmol), $[RuCl_2(p\text{-cymene})]_2$ (12.3 mg, 0.02 mmol), and pent-1-en-3-one (84.0 mg, 1.0 mmol) in 3.0 mL of dioxane/H_2O = 100:1 (v/v). The solution turned orange immediately, and then the mixture was stirred at 90 °C for 10 h. The reaction mixture was concentrated, and the residue was purified by silica gel chromatography (PE/EA = 100:1) to give the product.

1-(4-(*tert*-Butyl)phenyl)pentan-3-one (3aa, 208 mg, 95%.). Light yellow liquid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.30 (d, J = 8.4 Hz, 2H), 7.12 (d, J = 8.4 Hz, 2H), 2.87 (t, J = 7.6 Hz, 2H), 2.73 (t, J = 7.6 Hz, 2H), 2.42 (q, J = 7.2 Hz, 2H), 1.30 (s, 9H), 1.05 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 210.9, 149.1, 138.3, 128.2, 125.6, 44.1, 36.3, 34.6, 31.65, 29.5, 8.0. HRMS (QTOF-ESI) calcd for $C_{15}H_{22}ONa$ (M + Na) 241.1568, found 241.1555.

1-(*o*-Tolyl)pentan-3-one (3ba, 113 mg, 64%; 162 mg, 92%). Colorless liquid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.18−7.04 (m, 4H), 2.89 (t, J = 7.6 Hz, 2H), 2.69 (t, J = 7.6 Hz, 2H), 2.43 (q, J = 7.2 Hz, 2H), 2.31 (s, 3H), 1.06 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 210.9, 139.5, 136.1, 130.5, 128.8, 126.5, 126.4, 42.8, 36.3, 27.4, 19.5, 8.1. HRMS (QTOF-ESI) calcd for $C_{12}H_{17}O$ (M + H) 177.1279, found 177.1262.

1-(*m*-Tolyl)pentan-3-one (3ca, 164 mg, 93%). Colorless liquid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.19−7.15 (m, 1H), 7.02 − 6.97 (m, 3H), 2.87 (t, J = 7.6 Hz, 2H), 2.72 (t, J = 7.6 Hz, 2H), 2.42 (q, J = 7.2 Hz, 2H), 2.32 (s, 3H), 1.05 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 210.8, 141.4, 138.2, 129.4, 128.6, 127.1, 125.5, 44.2, 36.3, 30.0, 21.6, 8.0. HRMS (QTOF-ESI) calcd for $C_{12}H_{17}O$ (M + H) 177.1279, found 177.1255.

1-(*p*-Tolyl)pentan-3-one (3da, 162 mg, 92%).[18] Colorless liquid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.08 (s, 4H), 2.86 (t, J = 7.6 Hz, 2H), 2.71 (t, J = 7.6 Hz, 2H), 2.40 (q, J = 7.2 Hz, 2H), 2.31 (s, 3H), 1.04 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 210.8, 138.3, 135.7, 129.4, 128.4, 44.2, 36.3, 29.7, 21.2, 8.0.

1-(4-Methoxyphenyl)pentan-3-one (3ea, 173 mg, 90%).[19] Pale yellow liquid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.09 (d, J = 8.4 Hz, 2H), 6.82 (d, J = 8.8 Hz, 2H), 3.78 (s, 3H), 2.84 (t, J = 8.0 Hz, 2H), 2.69 (t, J = 7.2 Hz, 2H), 2.39 (q, J = 7.2 Hz, 2H), 1.03 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 211.0, 158.2, 133.4, 129.4, 114.1, 55.4, 44.4, 36.3, 29.2, 8.0.

1-(Naphthalen-1-yl)pentan-3-one (3fa, 72 mg, 34%; 199 mg, 94%).[20] Colorless viscous oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.00 (d, J = 8.0 Hz, 1H), 7.86 (d, J = 8.0 Hz, 1H), 7.72 (d, J = 8.0 Hz, 1H), 7.55−7.46 (m, 2H), 7.43 − 7.32 (m, 2H), 3.37 (t, J = 7.6 Hz, 2H), 2.86 (t, J = 7.6 Hz, 2H), 2.42 (q, J = 7.2 Hz, 2H), 1.06 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 210.9, 137.5, 134.1, 131.8, 129.1, 127.2, 126.3, 125.8, 125.8, 123.7, 43.4, 36.4, 27.1, 8.1.

1-(4-(Trifluoromethyl)phenyl)pentan-3-one (3ga, 208 mg, 90%). Pale yellow liquid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.52 (d, J = 8.0 Hz, 2H), 7.29 (d, J = 8.0 Hz, 2H), 2.96 (t, J = 7.6 Hz, 2H), 2.75 (t, J = 7.6 Hz, 2H), 2.41 (q, J = 7.2 Hz, 2H), 1.05 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 210.1, 145.6, 128.9, 128.7, 128.4, 125.9, 125.5, 125.5, 123.2, 43.4, 36.2, 29.6, 7.8. HRMS (QTOF-ESI) calcd for $C_{12}H_{14}F_3O$ (M + H) 231.0997, found 231.0988.

1-(4-Chlorophenyl)pentan-3-one (3ha, 180 mg, 92%).[21] Colorless liquid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.25−7.21 (m, 2H), 7.13−7.08 (m, 2H), 2.86 (t, J = 7.2 Hz, 2H), 2.70 (t, J = 7.2 Hz, 2H), 2.40 (q, J = 7.2 Hz, 2H), 1.04 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 210.3, 139.9, 131.9, 129.9, 128.7, 43.7, 36.3, 29.3, 7.9.

1-(4-(Trifluoromethoxy)phenyl)pentan-3-one (3ia, 232 mg, 94%). Colorless liquid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.21−7.18 (m, 2H), 7.12−7.10 (m, 2H), 2.90 (t, J = 7.2 Hz, 2H), 2.72 (t, J = 7.2 Hz, 2H), 2.41 (q, J = 7.2 Hz, 2H), 1.04 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 210.2, 147.7, 140.2, 129.8, 124.5, 122.0, 121.1, 119.4, 116.9, 43.6, 36.2, 29.1, 7.8. HRMS (QTOF-ESI) calcd for $C_{12}H_{14}F_3O_2$ (M + H) 247.0946, found 247.0936.

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1-(Benzo[*d*][1,3]dioxol-5-yl)pentan-3-one (3ja, 194 mg, 94%). Colorless liquid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.71 (d, J = 7.6 Hz, 1H), 6.67−6.66 (m, 1H), 6.63−6.61 (m, 1H), 5.91 (s, 2H), 2.81 (t, J = 7.4 Hz, 2H), 2.68 (t, J = 7.4 Hz, 2H), 2.39 (q, J = 7.2 Hz, 2H), 1.04 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 210.8, 147.8, 146.0, 135.2, 121.2, 109.0, 108.4, 101.0, 44.3, 36.3, 29.8, 8.0. HRMS (QTOF-ESI) calcd for $C_{12}H_{14}O_3Na$ (M + Na) 229.0841, found 229.0801.

1-Phenylpentan-3-one (3ka, 143 mg, 89%).[22] Colorless liquid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.30−7.26 (m, 2H), 7.22−7.14 (m, 3H), 2.91 (t, J = 7.6 Hz, 2H), 2.73 (t, J = 7.6 Hz, 2H), 2.41 (q, J = 7.2 Hz, 2H), 1.05 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 210.8, 141.4, 128.7, 128.6, 126.3, 44.1, 36.3, 30.1, 8.0.

(*E*)-7-Phenylhept-6-en-3-one (3la, 108 mg, 57%).[23] Colorless liquid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.35−7.27(m, 4H), 7.22−7.18 (m, 1H), 6.41 (d, J = 15.6 Hz, 1H), 6.24−6.18 (m, 1H), 2.64−2.57 (m, 2H), 2.51−2.42 (m, 4H), 1.07 (t, J = 7.4 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 211.0, 137.7, 130.9, 129.3, 128.8, 127.3, 126.2, 42.0, 36.3, 27.4, 8.1.

3-(4-(*tert*-Butyl)phenyl)-1-(*p*-tolyl)propan-1-one (3ab, 190 mg, 68%; 258 mg, 92%). White solid (mp 63.6−64.0 °C). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.87 (d, J = 8.0 Hz, 2H), 7.35−7.32 (m, 2H), 7.27−7.19 (m, 4H), 3.28 (t, J = 7.6 Hz, 2H), 3.04 (t, J = 7.6 Hz, 2H), 2.41 (s, 3H), 1.32 (s, 9H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 199.3, 149.1, 144.0, 138.6, 134.7, 129.5, 128.4, 128.4, 125.7, 40.6, 34.6, 31.7, 29.9, 21.9. HRMS (QTOF-ESI) calcd for $C_{20}H_{25}O$ (M + H) 281.1905, found 281.1869.

1-(4-(*tert*-Butyl)phenyl)-5-phenylpentan-3-one (3ac, 270 mg, 92%). Colorless viscous oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.32−7.26 (m, 4H), 7.22−7.15 (m, 3H), 7.13−7.08 (m, 2H), 2.91−2.84 (m, 4H), 2.73−2.69 (m, 4H), 1.31 (s, 9H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 209.6, 149.2, 141.3, 138.2, 128.8, 128.6, 128.2, 126.4, 125.6, 44.8, 34.6, 31.7, 30.0, 29.5. HRMS (QTOF-ESI) calcd for $C_{21}H_{26}ONa$ (M + Na) 317.1881, found 317.1868.

***n*-Butyl 3-(4-(*tert*-Butyl)phenyl)propanoate (3ad, 196 mg, 75%).** Colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.33−7.29 (m, 2H), 7.24−7.20 (m, 3H), 4.09 (t, J = 8.0 Hz, 2H), 2.98 (t, J = 8.0 Hz, 2H), 2.65 (t, J = 8.0 Hz, 2H), 1.57−1.62 (m, 2H), 1.33−1.39 (m, 2H), 0.92 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.4, 149.2, 128.2, 126.1, 125.6, 64.5, 36.2, 31.6, 31.4, 30.9, 30.7, 19.4, 14.0. HRMS (QTOF-ESI) calcd for $C_{17}H_{26}O_2Na$ (M + Na) 285.1831, found 285.1837.

3-(4-(*tert*-Butyl)phenyl)cyclopentanone (3ae, 89 mg, 41%; 166 mg, 77%). Beige solid (mp 79.9−80.3 °C). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40−7.34 (m, 2H), 7.23−7.15 (m, 2H), 3.44−3.35 (m, 1H), 2.69−2.63 (m, 1H), 2.50−2.43 (m, 2H), 2.38−2.45 (m, 2H), 2.04−1.93 (m, 1H), 1.32 (s, 9H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 218.7, 149.8, 140.3, 126.7, 125.8, 46.1, 42.0, 39.2, 34.7, 31.7, 31.5. HRMS (QTOF-ESI) calcd for $C_{15}H_{21}O$ (M + H) 217.1592, found 217.1573.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

NMR and/or HPLC spectra of compounds **1**−**3**. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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