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Carbonylative Addition of Arylboronic Acids to Terminal Alkynes: A New Catalytic Access to α,β-Unsaturated Ketones

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Abstract: The carbonylative addition of arylboronic acids to terminal alkynes under mild conditions affords (*E*)-α,β-unsaturated ketones with good yields. The reaction was achieved with chloro(1,5-cyclooctadiene)rhodium(I) dimer or chlorodicarbonylrhodium(I) dimer as catalytic precursor without additional phosphine as their use inhibits the reaction. Experiments using deuterated 1-hexyne discarded the possibility of a rhodium-vinylidene intermediate, thus a catalytic cycle involving a 1,2-insertion of the terminal alkyne in a rhodium-acyl bond is proposed. This new reaction represents the first example of the hydroacylation of terminal alkynes involving rhodium-acyl reagents generated under CO pressure and promises a wide field of interest.

Keywords: alkynes; carbonylation; C–C bond formation; rhodium; α,β-unsaturated carbonyl compounds

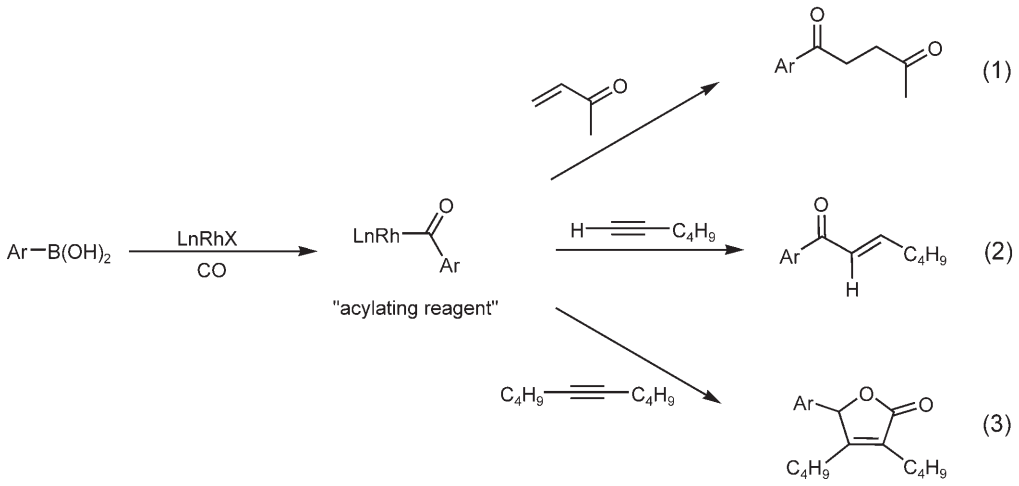
Introduction

α,β-Unsaturated ketones are important key reagents in organic synthesis. As typical examples, they are widely used as Michael acceptors in numerous catalysed 1,4-addition reactions,[1] or as activated olefins in Heck-type couplings[2] or in epoxidation reactions.[3] They are commonly synthesised through an aldol condensation reaction between one equivalent of ketone and one equivalent of an aldehyde derivative followed by a dehydration step.[4] The reaction is extremely efficient when acetophenone derivatives are used for chalcone synthesis. Nevertheless, it shows limitations when the aldehyde has an α-hydrogen and leads to the synthesis of α,β-unsaturated ketones being less straightforward. Alternative strategies are also available to access this latter family and among them, the most efficient ones appear to be the selective oxidation of an allylic alcohol[5] and Friedel–Crafts acylation reaction of arenes using α,β-unsaturated acyl chlorides.[6] In that context, only a limited number of reactions involve a carbonylation step and most of them, such as the Pauson–Khand reaction, give access to cyclic-α,β-unsaturated ketones.[7]

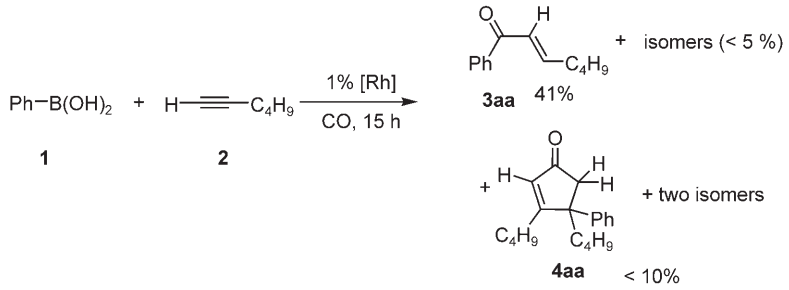
Molecules obtained from cascade-like reactions where carbon monoxide is the only source of carbonyl function would be an interesting catalytic process. This procedure would not only be economically viable in terms of atomic yield, but also valuable from an environmental point of view, as this insertion does not yield any by-product.

The rhodium-catalysed 1,4-addition of arylboronic acids to α,β-unsaturated ketones has opened a new area of investigation for the development of new C–C bond forming reactions.[8] The key step of that reaction involves a transmetalation of the aryl moiety from a boron species to the rhodium centre and leads to suitable metal-carbon-containing catalytic intermediates.[9] This reactivity has been more recently exploited for the development of other rhodium-catalysed reactions like the addition of arylboronic acids to alkynes.[10] Rhodium complexes containing Rh–C bonds are otherwise well-known to readily insert carbon monoxide and yield metal-acyl complexes.[11] These are known to react with olefins[12] for ketones synthesis although they are not easily obtained through the activation of the C–H bond in aldehydes. With these two concepts in mind, we recently investigated the possibility of performing the carbonylative 1,4-addition of arylboronic acids to enones [Scheme 1, Eq.(1)].[13]

This new transformation efficiently yields 1,4-diketones and offers a fast access to 2,5-disubstituted pyrroles or furans when the carbonylation reaction is followed by cyclisation.[14] This reaction is one of the rare examples of a nucleophilic acylating reagent catalytically generated from carbon monoxide.[15] As continuation of this work, we thus anticipated that this reactivity could be enlarged to alkynes. We now report that arylboronic acids react with terminal alkynes under carbon monoxide pressure to yield selectively α,β-unsaturated ketones if appropriate condi-



Scheme 1. Carbonylative addition of arylboronic acid to enones and alkynes.



Scheme 2. Products obtained through carbonylative addition of phenylboronic acid to a terminal alkyne, 1-hexyne.

tions are used [Scheme 1, Eq. (2)]. This transformation is formally a hydroacylation of alkynes and is a very rare example of a reaction involving carbon monoxide as the carbonyl source.[16] However, in the course of our work, the catalytic carbonylative addition reaction of phenylboronic acids on internal alkynes yielding 5-aryl-2(5*H*)-furanones was reported [Scheme 1, Eq. (3)]. Even thought this reaction does not yield α,β-unsaturated ketones, it likely involves an acylation step before the cyclisation yielding the 5-aryl-2(5*H*)-furanones.[17]

Results and Discussion

The reaction between one equivalent of phenylboronic acid and one equivalent of 1-hexyne in methanol at 80 °C under 5 bar CO in the presence of 0.5 % of $[Rh(COD)Cl]_2$ (COD = 1,5-cyclooctadiene) showed the formation of α,β-unsaturated ketone **3aa** as the major product in 41 % yield (Scheme 2).

The structure of the obtained compound was confirmed by ^1H and ^{13}C NMR spectroscopy. Moreover, the coupling constant between the two olefinic protons is consistent with an *E* configuration of the double bond ($^3J_{H,H} = 15$ Hz). The formation of the α,β-unsaturated ketone is accompanied by the formation of side products in low yields. The analysis of the mixture by gas chromatography/mass spectrometry (GC/MS) with electron impact and chemical ionisation, evidenced the formation of less than 5% of derivatives having the same molecular weight as the main product **3aa** ($m/z = 188$, $[M^+]$). These compounds, obtained in low yields, can be attributed to the isomers of **3aa** with a *Z* double bond configuration or the branched derivative. GC-MS analysis also show the presence of three higher molecular weight derivatives in less than 10% yield which have the same molecular weight ($m/z = 270$, $[M^+]$). Actually, this molecular weight fits with the mass of compounds including one phenyl moiety, a CO unit and two hexyne units. Various attempts to separate these isomers were only successful with compound **4aa**. ^1H and ^{13}C NMR analysis of this product allowed us to determine its configuration as represented in Scheme 2. It is noteworthy that in all the experiments run in the course of this study, neither the corresponding furanone, nor hex-1-enylbenzene (the product of direct addition of the phenylboronic acid to 1-hexyne without CO insertion) were observed.

The formation of all these side products in low amounts does not account for the mass balance. Since

Table 1. Carbonylative addition of phenylboronic acid to 1-hexyne **2a**, effect of the reaction conditions on the yield in **3aa**.[a]

Entry	**1a** (mmol)	Solvent	T [°C]	P(CO) [bar]	1-Hexyne conversion [%]	**3aa** [%][b]
1	1.5	methanol	80	5	>90	41
2	2.3	methanol	80	5	>90	57
3	2.3	methanol	80	10	>90	52
4	2.3	methanol	80	20	>90	32
5	2.3	methanol	60	5	46	16
6	2.3	methanol	100	5	>90	46
7	2.3	1-propanol	80	5	>90	10
8	2.3	CF_3CH_2OH	80	5	10	traces
9	2.3	toluene	80	5	>90	traces
10	2.3	DMF	80	5	>90	1
11	2.3	THF	80	5	>90	traces

[a] The reactions were performed in 10 mL of solvent with 0.5% of $[Rh(COD)Cl]_2$ for 18 h.
[b] Yields were determined by GC using undecane as internal standard and based on phenylboronic acid.

the GC analysis of the crude shows the complete disappearance of 1-hexyne, the moderate yield of **3aa** can likely be attributed to polymerisation of the alkyne in the presence of the rhodium-based catalyst.[18] This competitive reaction led us to perform the reaction using an excess of 1-hexyne (2.3 mmol of 1-hexyne *vs.* 1.5 mmol of phenylboronic acid). Under these new conditions, the yield calculated from phenylboronic acid increased from 41% to 57% and the starting 1-hexyne once again completely disappeared (Table 1, entries 1 and 2). Additional experiments showed that the use of much higher quantities of starting 1-hexyne does not improve the global yield in **3aa**. The influence of the reaction conditions on the yield in α,β-unsaturated ketone was also studied with phenylboronic acid and 1-hexyne as model substrates (Table 1).

The CO pressure needs to be well tuned to achieve the highest yield of **3aa**. When the pressure was increased from 5 to 20 bar, the yield of the expected α,β-unsaturated ketone gradually decreased from 57% to 32% (entries 2–4). On the other hand, if a lower pressure was used, the formation of higher molecular weight derivatives **4** increased and the overall yield of **3aa** decreased once more. 80 °C proved to be the optimal reaction temperature. Higher or lower temperatures led to markedly lower yields (entries 2, 5, 6). At 60 °C, the reaction rate was probably too slow to achieve a high yield within 18 h. At this temperature, even the polymerisation process was limited to a 46% conversion. Methanol allowed much higher yields than any other organic solvents and appears to be the medium of choice to perform the reaction (entries 2, 7–10). Other alcohols such as 1-propanol or trifluorethanol gave much lower yields. Using THF or DMF, as well as non-polar solvents like toluene, gave only traces of ketone **3aa**.

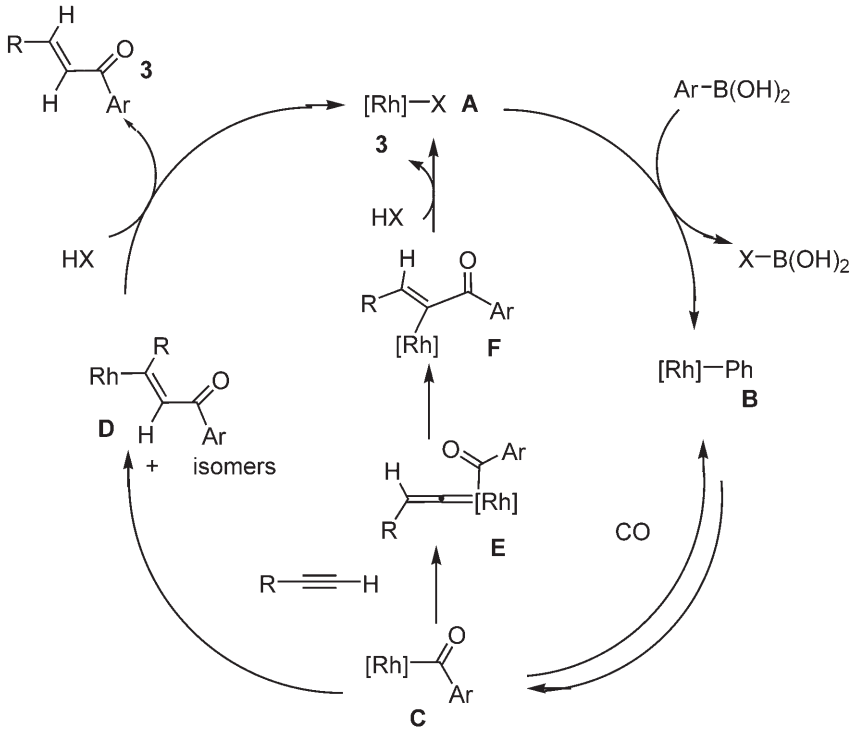
Other rhodium complexes have been evaluated to determine the best catalyst precursor (Table 2). The reactions were carried out starting from 2.3 mmol of 1-hexyne, 1.5 mmol of phenylboronic acid in 10 mL MeOH under 5 bar CO pressure, using the same amount of rhodium in all the experiments (1% of rhodium).

Table 2. 1,4-Carbonylative addition of phenylboronic acid to 1-hexyne, influence of the catalyst precursor on the yield in **3aa**.[a]

Entry	Catalyst	**3aa** [%][b]
1	0.5% $[Rh(COD)OH]_2$	0
2	0.5% $[Rh(COD)OMe]_2$	0
3	1% $HRh(CO)(PPh_3)_3$	0
4	1% $Rh(acac)(CO)_2$	0
5	1% $[Rh(COD)_2][BF_4]$	0
6	1% $RhCl_3$, 3 H_2O	3
7	0.5% $[Rh(C_2H_4)_2Cl]_2$	8
8	0.5% $[Rh(CO)_2Cl]_2$	57
9	0.5% $[Rh(COD)Cl]_2$	43
10	0.5% $[Rh(COD)Cl]_2$ + 2.5% COD	39
11	1% $ClRh(PPh_3)_3$	11
12	0.5% $[Rh(COD)Cl]_2$ + 1% $P(C_6F_5)_3$	17
13	0.5% $[Rh(COD)Cl]_2$ + 1% PPh_3	16
14	1% ClRh(CO)dppp	16
15	0.25% $Rh_4(CO)_{12}$	<2

[a] The reactions were performed with 1.5 mmol arylboronic acid, 2.3 mmol 1-alkyne and 1% of rhodium catalyst in 10 mL of MeOH under 5 b CO at 80 °C for 18 h.
[b] Yields were determined by GC using undecane as internal standard and based on phenylboronic acid.

In contrast with the reaction involving methyl vinyl ketone[13,14], most of the rhodium precursors were inefficient and led to inactive catalysts (entries 1–6). The best precursors were rhodium chloride dimers containing carbon monoxide (CO) or 1,5-cyclooctadiene (COD). To the best of our knowledge, the COD is easily replaced by CO under pressure.[19] The use of an excess of COD (in order to stabilize Rh-



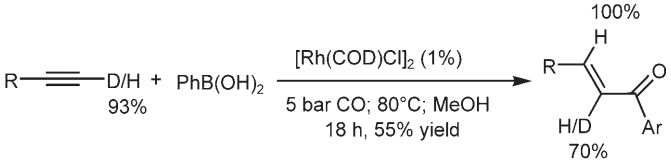
Scheme 3. Proposed catalytic cycle for the carbonylative addition of an arylboronic acid to a terminal alkyne.

COD complexes by shifting the equilibrium toward these compounds[20]) did not give rise to a better reactivity (entries 8–10). All rhodium complexes with phosphines were much less efficient and afforded limited yields of **3aa** from 11% to 17% (entries 11–14). We investigated the use of $Rh_4(CO)_{12}$, as simple, commercially available cluster, but this precursor was completely ineffective.

Scheme 3 depicts two proposed catalytic cycles for this transformation. Starting from derivative **A**, a first step would involve the transmetallation of the aryl from the boron to the rhodium centre giving a rhodium-aryl species (compound **B**).

B can insert a CO moiety yielding a metal-acyl complex **C** as the key intermediate for this family of reactions. As usual for this type of insertion, the phenomenon is likely reversible and the decarbonylation step is moreover well documented.[21] One would expect under these reaction conditions that the rhodium-aryl complex **B** will directly react with the alkyne and thus generate an aryl-substituted alkyne. This reaction which has been only described with internal alkynes[22] was never observed in our case. In a further step, two different pathways can be envisaged from **C** to yield **3**. The newly generated rhodium-acyl complex **C** can react with the alkyne, giving a new rhodium intermediate **D.** Depending on the insertion type of the alkyne (head to head, head to tail and tail to tail), several isomeric structures of **D** can be envisaged. Alternatively, the reaction between a rhodium complex **C** and a terminal alkyne can lead to a rhodium vinylidene intermediate **E** as suggested by Lee et al. in a reaction involving an addition step of an aryl to a terminal alkyne.[17d] The α-migration of the acyl moiety to the vinylidene ligand yields the intermediate **F**. Finally, compound **D** or **F** can be directly protonated leading to the same product **3**. In order to determine which pathway is involved in our transformation, a standard reaction has been performed between phenylboronic acid and deuterated 1-hexyne (95% D) in MeOH (Scheme 4).

After one overnight reaction the product was purified by silica gel column chromatography and analysed by ^{1}H NMR spectroscopy. The ^{1}H NMR spectrum of the resulting α,β-unsaturated ketone clearly evidenced the exclusive deuterium incorporation at the α-position of the carbonyl group (70% D). Although the recovery of deuterium to this position was



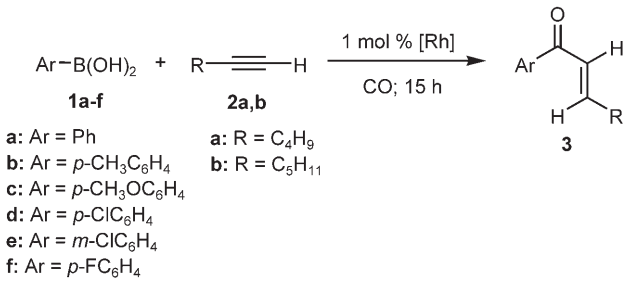
Scheme 4. Carbonylative addition of phenylboronic acid to a deuterated terminal alkyne.

incomplete, probably due to an MeOH-hexyne proton exchange in the course of the reaction, this observation clearly discards a pathway involving a rhodium vinylidene intermediate in favour of a 1,2-migration process. The protonation thus occurs at the β-position of the enone and several proton donors may be involved in this final step.[15] The arylboronic acid itself or the water generated *via* the dehydration of arylboronic acid in the cyclic trimer anhydride can act as good proton donors. Another possibility arises from the protic nature of methanol which would favour this last step; this would be consistent with the fact that other solvents induce lower yields in **3aa**.

On the other hand, the detection by GC-MS of higher molecular weight derivatives **4** is related to a side reaction involving intermediate **B**. Further 1-alkyne insertion remains, however, limited as no other higher oligomers were detected by GC-MS analysis.

Finally, in order to delineate the scope and limitations of this reaction, various 1-alkynes and arylboronic acids were allowed to react using the standard procedure (Scheme 5 and Table 3). The reaction products were purified by silica gel column chromatography with the appropriate eluent.

The results obtained show that the chain size of the alkyne plays an important role on the efficiency of the reaction. A 57% yield of **3aa** is obtained if phenylboronic acid is reacted with 1-hexyne compared to 41% yield of **3ab** with 1-heptyne.[23] A similar trend is observed with *p*-tolylboronic acid, 1-hexyne or 1-heptyne, yielding enones **3ba** and **3bb** in 69% and 47% yields, respectively. The nature of the substituents on the phenyl group also has an important impact on the yield of enones **3**. Electron-donating substituents lead to the highest yields in compounds **3**. The enones **3ba** and **3ca** obtained from the *p*-tolylboronic acid or *p*-methoxyphenylboronic acid were isolated in, respectively, 69% and 70% yields compared to 57% with phenylboronic acid. In contrast, using aryl groups bearing electron-withdrawing substituents gave lower yields. Enones **3da** and **3fa** synthesised from *p*-chlorophenylboronic acid or *p*-fluorophenylboronic acid are obtained in 45% and 51% yield. The *meta*-substitution of the chloride on the phenyl ring led to a poor reactivity since derivative **3ea** is only obtained in 27% yield. A similar trend concerning the aryl substituents effect was reported in the case of the carbonylative 1,4-addition reaction of arylboronic acids to internal alkynes or methyl vinyl ketone.[14,18] In the case of the reactivity of methyl vinyl ketone, this effect could be correlated to the lower selectivity of carbonylated *versus* non-carbonylated reaction products. Such a comparison cannot be made in this case since no non-carbonylated product are observed but this likely comes from the well established lower ability of carbon monoxide to insert into the metal-aryl bond when the aryl moieties are substituted with electron-withdrawing groups.[24]



Scheme 5. Carbonylative addition of various arylboronic acids to terminal alkynes.

Table 3. 1,4-Carbonylative addition of various arylboronic acids to terminal alkynes.[a]

Entry	Ar	R	**3** (%)[b]
1	C_6H_5	C_4H_9	**3aa** (57)
2	*p*-CH_3-C_6H_4	C_4H_9	**3ba** (69)
3	C_6H_5	C_5H_{11}	**3ab** (41)
4	*p*-CH_3-C_6H_4	C_5H_{11}	**3bb** (47)
5	*p*-CH_3O-C_6H_4	C_4H_9	**3ca** (70)
6	*p*-Cl-C_6H_4	C_4H_9	**3da** (45)
7	*m*-Cl-C_6H_4	C_4H_9	**3ea** (27)
8	*p*-F-C_6H_4	C_4H_9	**3fa** (51)

[a] Conditions: same as in Table 2, using 1 mol% [Rh(COD)Cl]$_2$ as catalyst precursor.
[b] Isolated yields based on arylboronic acid.

Conclusions

We have developed a new reaction, namely the rhodium-catalysed carbonylative addition reaction of arylboronic acids to terminal alkynes. The reaction enables the synthesis of α,β-unsaturated ketones **3**, rather than 5-aryl-2(5*H*)-furanones, with carbon monoxide as carbonyl source. This catalytic reaction is a further example of the use of a metal-acyl intermediate generated from carbon monoxide and an organoboron derivative for organic synthesis. Further studies are in progress aimed at both mechanistic aspects of the reaction and applications of carbonylation reactions using arylboronic acids and other co-reactants as substrates.

Experimental Section

General Remarks

All reactions were performed under a dry carbon monoxide and nitrogen atmosphere. Methanol was distilled from Mg

and stored under nitrogen prior to use. Terminal alkynes and arylboronic acids were purchased from Sigma–Aldrich. The alkynes were distilled from CaH_2 prior to use. ^1H and ^{13}C NMR spectra were recorded in $CDCl_3$ at room temperature on a Bruker AV300 spectrometer at 300 MHz. Chemical shifts were determined relative to internal standard peaks and deuterated solvents (TMS at $\delta = 0$ ppm for protons, $CDCl_3$ at $\delta = 77.23$ ppm for carbon atoms). GC analyses for yield determinations were performed on a Varian 3900 chromatograph. Flash chromatography for product purifications was performed using silica gel (Macherey–Nagel, 60 Å, 230–400 mesh). Deuterated hexyne was prepared by D_2O–1-hexyne proton/deuterium exchange according to a literature procedure.[25]]

GC/MS Analysis

GC/MS, using both electron impact (EI) and chemical ionisation (CI) techniques was used to analyse the crude of reaction involving phenylboronic acid and 1-hexyne. CI was used in order to confirm the molecular mass of those compounds detected using EI/MS.

GC conditions: Gas chromatography was performed on a Trace GC (Thermoelectron, San Jose, USA). A RTx-5 MS (Restek, Evry, France) column 30 m × 0.25 mm i.d × 0.25 μm df was used for the analysis with a helium carrier gas flow of 1 mL min^{-1}. The GC oven initial temperature was 80 °C and temperature was ramped first at 10 °C min^{-1} to 230 °C and then at 5 °C min^{-1} to 280 °C where it was held for 15 min. A 1 μL injection with a 1:100 split was used, the injector temperature was fixed at 280 °C.

MS conditions: MS analysis were performed on a Polaris Q from Thermoelectron (San Jose, USA).The instrument was calibrated using FC43 (perfluorotributylamine) as reference. The chemical ionisation (CI) reagent gas was methane with a 2 mL min^{-1} flow rate. Mass spectra were acquired over the range m/z 40 to 450 in positive ionisation mode. The source temperature is 200 °C.

General Procedure of Carbonylative Addition of Arylboronic Acids to Terminal Alkynes

Arylboronic acid (1.5 mmol) and rhodium catalyst (1%) were introduced in a 100-mL stainless steel autoclave with a glass insert tube and purged three times with nitrogen. In a Schlenk tube flushed with nitrogen, the terminal alkyne (2.3 mmol) and the internal standard (142 μL) were dissolved in methanol (10 mL). The solution was transferred with a syringe into the autoclave, which was then pressurised with 5 bar of carbon monoxide and heated at 80 °C with a water bath. After 18 h, the autoclave was cooled to room temperature and depressurised. The pure products were isolated by flash chromatography (*n*-hexane/diethyl ether: 95/5).

3aa: 1-phenyl-hept-2-en-1-one: ^1H NMR (300 MHz, $CDCl_3$): $\delta = 7.92$ (d, $^3J_{H,H} = 7.3$ Hz, 2H, CH_{arom}), 7.55 (t, $^3J_{H,H} = 7.3$ Hz, 1H,), 7.46 (t, $J = 7.7$ Hz, 2H, CH_{arom}), 7.07 (dt, $J = 7.0$ and 15.3 Hz, 1H, C*H*=CHCO), 6.87 (d, $^3J_{H,H} =$ 15.3 Hz, 1H, CH=C*H*CO), 2.31 (q, $^3J_{H,H} = 7.0$ Hz, 2H, COCH_2CH$_2$), 1.44 (m, 4H, CH_2), 0.93 (t, $^3J_{H,H} = 7.1$ Hz, 3H, CH_3); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 190.9$, 150.1, 138.0, 132.6, 128.5, 125.9, 32.6, 30.3, 22.3, 13.9; MS: m/z (%) = 189 (11) $[M+1]^+$, 188 (35) $[M]^+$, 173 (35), 159 (34), 145 (44), 131 (44), 117 (23), 105 (100), 91 (19), 77 (63), 65 (2), 55 (21).

3ab: 1-phenyl-oct-2-en-1-one: ^1H NMR (300 MHz, $CDCl_3$): $\delta = 7.85$ (d, $^3J_{H,H} = 7.2$ Hz, 2H, CH_{arom}), 7.47 (t, $^3J_{H,H} = 7.3$ Hz, 1H, CH_{arom}), 7.38 (t, $^3J_{H,H} = 7.7$ Hz, 2H, CH_{arom}), 6.99 (dt, $^3J_{H,H} = 15.4$ and 6.9 Hz, 1H, C*H*=CHCO), 6.79 (d, $^3J_{H,H} = 15.5$ Hz, 1H, CH=C*H*CO), 2.23 (q, $^3J_{H,H} =$ 7.7 Hz, 2H, CH_2), 1.44 (t, $^3J_{H,H} = 7.2$ Hz, 2H, CH_2), 1.25 (m, 4H, CH_2), 0.82 (t, $^3J_{H,H} = 6.9$ Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 190.9$, 150.2, 138, 132.6, 128.5, 128.1, 125.8, 32.8, 31.4, 27.9, 22.5, 14

3ba: 1-*p*-tolyl-hept-2-en-1-one: ^1H NMR (300 MHz, $CDCl_3$): $\delta = 7.84$ (d, $^3J_{H,H} = 8.1$ Hz, 2H, CH_{arom}), 7.26 (d, $^3J_{H,H} = 7.8$ Hz, 2H, CH_{arom}), 7.05 (m, 1H, C*H*=CHCO), 6.88 (d, $^3J_{H,H} = 15.5$ Hz, 1H, CH=C*H*CO), 2.41 (s, 1H, CH_3), 2.31 (q, $^3J_{H,H} = 7.1$ Hz, 2H, COCH_2CH$_2$), 1.44 (m, 4H, CH_2), 0.93 (t, $^3J_{H,H} = 7.1$ Hz, 3H, CH_3); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta =$ 190.4, 149.5, 143.3, 135.4, 129.2, 128.7, 125.8, 32.5, 30.3, 22.3, 21.6, 13.9; MS: m/z (%) = 203 (12) $[M+1]^+$, 202 (24) $[M]^+$, 187 (35), 173 (14), 159 (20), 148 (29), 145 (28), 131 (17), 119 (100), 91 (54), 81 (7), 65 (15), 55 (8).

3bb: 1-*p*-tolyl-oct-2-en-1-one: ^1H NMR (300 MHz, $CDCl_3$): $\delta = 7.77$ (d, $^3J_{H,H} = 8.2$ Hz, 2H, CH_{arom}), 7.18 (d, $^3J_{H,H} = 7.9$ Hz, 2H, CH_{arom}), 6.98 (dt, $^3J_{H,H} = 15.5$ and 6.7 Hz, 1H, C*H*=CHCO), 6.80 (d, $^3J_{H,H} = 15.4$ Hz, 1H, CH=C*H*CO), 2.33 (s, 3H, CH_3), 2.22 (q, $^3J_{H,H} = 7$ Hz, 2H, COCH_2CH$_2$), 1.4 (qt, $^3J_{H,H} = 7.3$ Hz, 2H, CH_2), 1.25 (m, 4H, CH_2), 0.82 (t, $^3J_{H,H} = 6.7$ Hz, 3H, CH_3); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta =$ 189.1, 148.2, 142.2, 133.5, 127.4, 126.9, 123.9, 30.8, 29.7, 26.2, 20.6, 18.8, 11.5.

3ca: 1-*p*-chlorophenyl-hept-2-en-1-one: ^1H NMR (300 MHz, $CDCl_3$): $\delta = 7.87$ (d, $^3J_{H,H} = 8.6$ Hz, 2H, CH_{arom}), 7.43 (d, $^3J_{H,H} = 8.5$ Hz, 2H, CH_{arom}), 7.08 (dt, $^3J_{H,H} = 15.5$ Hz and 6.3 Hz, 1H, C*H*=CHCO), 6.84 (d, $^3J_{H,H} = 15.4$ Hz, 1H, CH=C*H*CO), 2.32 (q, $^3J_{H,H} = 6.7$ Hz, 2H, COCH_2CH$_2$), 1.25–1.56 (m, 4H, CH_2), 0.93 (t, $^3J_{H,H} = 7.2$ Hz, 3H, CH_3); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 189.6$, 150.8, 139, 136.3, 129.9, 128.8, 125.4, 32.6, 30.3, 22.3, 13.9 MS: m/z (%) = 223 (13) $[M+1]^+$, 222 (26) $[M]^+$, 207 (21), 193 (26), 187 (16), 179 (14), 168 (23), 154 (19), 141 (36), 139 (100), 115 (15), 111 (32), 81 (16), 75 (22), 55 (17).

3da: 1-*p*-methoxyphenyl-hept-2-en-1-one: ^1H NMR (300 MHz, $CDCl_3$): $\delta = 7.86$ (d, $^3J_{H,H} = 6.9$ Hz, 2H, CH_{arom}), 6.96 (m, 1H, C*H*=CHCO), 6.85 (d, $^3J_{H,H} = 7$ Hz, 2H, CH_{arom}), 6.80 (d, $^3J_{H,H} = 17$ Hz, 1H, CH=C*H*CO), 3.77 (s, 3H, OCH_3), 2.22 (q, $^3J_{H,H} = 6.7$ Hz, 2H, COCH_2CH$_2$), 1.35 (m, 4H, CH_2), 0.84 (t, $^3J_{H,H} = 5.2$ Hz, 3H, CH_3); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 189.1$, 163.2, 149, 130.83, 130.79, 125.5, 113.7, 55.4, 32.5, 30.3, 22.3, 13.9; MS: m/z (%) = 219 (6) $[M+1]^+$, 218 (22) $[M]^+$, 189 (10), 175 (23), 164 (37), 150 (14), 135 (100), 121 (4), 107 (10), 92 (7), 77 (19), 63 (4), 55 (3).

3ea: 1-(3-chlorophenyl)-hept-2-en-1-one: ^1H NMR (300 MHz, $CDCl_3$): $\delta = 7.79$ (s, 1H, CH_{arom}), 7.70 (d, $^3J_{H,H} =$ 7.5 Hz, 1H, CH_{arom}), 7.40 (t, $^3J_{H,H} = 7.7$ Hz, 1H, CH_{arom}), 7.3 (t, $^3J_{H,H} = 7.09$ Hz, 1H), 7.09 (dt, $^3J_{H,H} = 15.2$ and 4.8 Hz, 1H), 6.72 (d, $^3J_{H,H} = 15.4$ Hz, 1H), 2.32 (q, $^3J_{H,H} = 6.9$ Hz, 2H, COCH_2CH$_2$), 1.42 (m, 4H, CH_2), 0.94 (t, $^3J_{H,H} = 5.3$ Hz, 3H, CH_3); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 189.4$, 151.1, 139.6, 134.8, 132.5, 129.8, 128.6, 126.6, 125.4, 32.6, 30.2, 22.3, 13.8; MS: m/z (%) = 223 (12) $[M+1]^+$, 222 (34) $[M]^+$, 207 (24), 193 (31), 187 (29), 179 (16), 168 (19), 158 (13), 154 (19), 145 (20), 141 (34), 139 (100), 131 (13), 115 (20), 111 (38), 81 (12), 75 (22), 55 (30).

3fa: 1-(4-fluorophenyl)-hept-2-en-1-one: ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 7.96$ (t, $^3J_{H,H} = 5.6$ Hz, 2H, CH_{arom}), 7.09 (m, 3H, CH_{arom} and C*H*=CHCO), 6.85 (d, $^3J_{H,H} =$ 15.4 Hz, 1H, CH=C*H*CO), 2.31 (q, $^3J_{H,H} = 6.8$ Hz, 2H), 1.43 (m, 4H), 0.93 (t, $^3J_{H,H} = 7.1$ Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 189.0$, 165.4 ($^1J_{C,F} = 254$ Hz), 150.2, 134.2 ($^4J_{C,F} =$ 13 Hz), 131.0 ($^3J_{C,F} = 37$ Hz), 125.3, 115.5 ($^2J_{C,F} = 87$ Hz), 32.5, 30.2, 22.3, 13.8; MS: *m*/*z* (%) = 207 (10) $[M+1]^+$, 206 (20) $[M]^+$, 191 (20), 177 (22), 163 (18), 152 (13), 149 (14), 138 (16), 123 (100), 109 (12), 95 (33), 81 (10), 75 (15), 55 (9).

4aa: 3,4-dibutyl-4-phenylcyclopent-2-enone: ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 7.18$ (m, 5H, CH_{arom}), 5.88 (s, 1H, CH_2C=C*H*-CO), 2.90 and 2.76 (AB system, 2H, CH_AH_B, $^2J = 18.8$ Hz), 2.37 (t, 2H, $^3J_{H,H} = 7.6$ Hz),1.83 [m, 2H, $CH_2C(Ph)$], 1.02–1.38 (m, 10H), 0.87 (t, 3H, $^3J_{H,H} = 7.3$ Hz), 0.78 (t, 3H, $^3J_{H,H} = 7.3$ Hz); ^{13}C NMR (300 MHz, $CDCl_3$): $\delta = 211.2$, 180.9, 143.2, 128.4, 127.9, 126.4, 126.3, 55.5, 46.5, 38.1, 33.1, 29.2, 26.8, 23.2, 22.5, 13.9, 13.8; MS: *m*/*z* (%) = 270 (5) $[M]^+$, 214 (100), 172 (72).

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