Rhodium-catalysed addition of organotrialkoxysilanes to α-substituted acrylic esters

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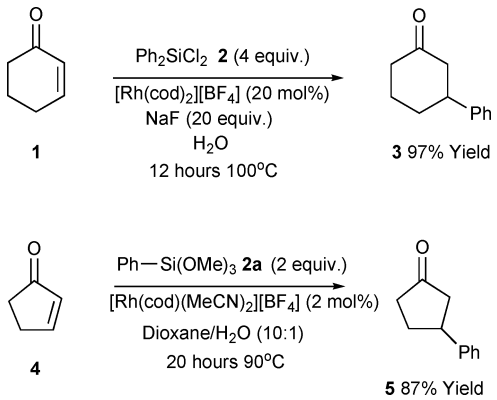
The cationic rhodium complex $[Rh(cod)_2][BF_4]$ effectively catalyses the 1,4-addition of organotrialkoxysilanes to α-substituted acrylic esters. The reactions are promoted by heating in an oil-bath or more conveniently in a microwave reactor allowing rapid access to a useful range of functionalised products including 2-alkyl succinates and α-amino acid derivatives.

Introduction

The transition-metal catalysed conjugate addition of organometallics to activated alkenes is regarded as fundamental methodology for organic synthesis.[1] Of particular importance is the elegant rhodium-catalysed addition of organoboron reagents to α,β-unsaturated carbonyl derivatives, pioneered by Hayashi and Miyaura.[2] This widely-used reaction can be carried out in aqueous solvent and affords excellent enantioselectivities (>90% ee) across a wide-range of substrates including α,β-unsaturated ketones, esters, amides, phosphonates and sulfones.[3] A successful catalytic conjugate addition is dependent on an efficient transmetalation to rhodium. Other organometallics that are known to participate in the key transmetalation to rhodium include organotin, organosilicon, organozinc, organozirconium, organotitanium, organobismuth and organoindium reagents.[4]

The utility of arylchlorosilanes in rhodium-catalysed conjugate additions has been reported. For example, the addition of diphenyldichlorosilane **2** to cyclohexenone **1** is achieved in the presence of a high-loading of cationic rhodium catalyst (Scheme 1).[5] The reaction proceeds in water as solvent but requires the addition of a large excess of fluoride salt for an efficient transformation to product **3**. Oi and Inoue have reported the additive-free conjugate addition of organotrialkoxysilanes.[6] The addition of phenyltrimethoxysilane **2a** to cyclopentenone **4** in the presence of just 2 mol% of cationic rhodium complex furnishes the product **5** in good yield. The conjugate addition of organotrialkoxysilanes can also be accomplished using palladium complexes.[7] More recently, the rhodium-catalysed enantioselective conjugate addition of organotrialkoxysilanes to α,β-unsaturated carbonyl compounds has been disclosed.[8] The use of organotrialkoxysilanes offers many of the advantages of boronic acids in terms of commercial availability, ease of handling and stability to air and moisture. Moreover, a number of straightforward synthetic routes have been reported for their preparation including the hydrosilylation of alkynes, the addition of Grignard reagents to tetraethyl orthosilicate and the cross-coupling of triethoxysilane with organohalides.[9]



Scheme 1 The rhodium-catalysed addition of organosilicon reagents.

The selective addition to α-substituted acrylic esters is more difficult than cyclic enones. This can be attributed to their lower reactivity and crucially, in the asymmetric process the enantioselectivity is determined at the protonation step of an oxa-π-allylrhodium intermediate and not at the insertion step (Fig. 1).[10] Herein we report the utility of the silicon–rhodium transmetalation process as a means to promote the conjugate addition of aryl nucleophiles to α-substituted acrylic esters. It was found the addition of organotrialkoxysilanes can be promoted by heating in an oil-bath or more conveniently in a microwave reactor allowing rapid access to a useful range of functionalised products including 2-alkyl succinates and α-amino acids.

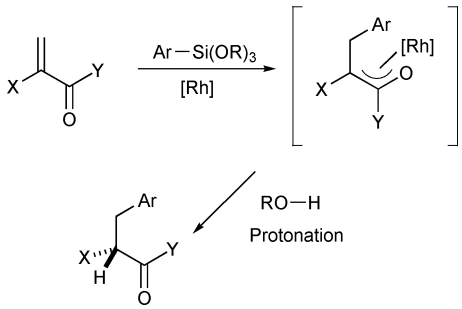


Fig. 1 The rhodium-catalysed addition to α-substituted acrylic esters.

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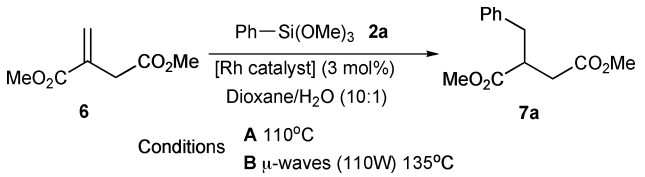
Results and discussion

Initially, the conjugate addition of phenyltrimethoxysilane **2a** to dimethyl itaconate **6** was examined in the presence of different rhodium complexes (Scheme 2).



Scheme 2 The rhodium-catalysed addition of phenyltrimethoxysilane.

The majority of organic reactions are heated using traditional heat transfer equipment such as oil baths and heating blocks. These heating techniques however are usually slower and do not provide uniform heating. In contrast, microwaves provide direct heating and radiation that passes through the reaction vessel, hence heating only the reactants and solvent. Therefore microwave irradiation provides fast heating rates and can enable rapid optimisation of numerous organic transformations including catalytic processes.[11] Investigations into the effect of catalyst, temperature and microwave irradiation on the rhodium-catalysed addition reaction were studied (Table 1).

In initial experiments, no product was observed using neutral rhodium catalysts such as $[RhCl(coe)_2]_2$ or $[RhCl(cod)]_2$ by reaction in the microwave reactor or by standard heating (Table 1, entries 1 and 2). This is in agreement with the previous report of Oi and Inoue that notes the necessity of cationic rhodium complexes to achieve an efficient transmetalation in the absence of added base.[6]

After heating for 24 hours in the presence of $[Rh(cod)_2][BF_4]$, substrate **6** was completely converted to product **7** (Table 1, entry 4). During the microwave experiments the reaction times were considerably shorter, and yet the reaction still proceeded to form the product in excellent conversion. Subsequently, we found that this was also true of the standard heating experiments (Table 1, entries 7–9). It was therefore pleasing to note that in 50 minutes both protocols afforded complete conversion to product. This is significantly more efficient than previous literature examples that are routinely run for 12–24 hours.

Table 1 Optimisation of reaction parameters

Entry	Conditions[a]	[Rh catalyst]	Time/min	Conversion[b] (%)
1	**A**	$[RhCl(coe)_2]_2$	1440	0
2	**A**	$[RhCl(cod)]_2$	1440	0
3	**A**	$[Rh(cod)_2][PF_6]$	1440	15
4	**A**	$[Rh(cod)_2][BF_4]$	1440	100
5	**A**	$[Rh(cod)_2][BF_4]$	50	100
6	**B**	$[RhCl(cod)]_2$	50	0
7	**B**	$[Rh(cod)_2][BF_4]$	30	60
8	**B**	$[Rh(cod)_2][BF_4]$	45	87
9	**B**	$[Rh(cod)_2][BF_4]$	50	100
10	**B**[c]	$[Rh(cod)_2][BF_4]$	50	100

[a] **A** Reactions were heated at 110 °C in the presence of 3 mol% [Rh] in dioxane–H_2O (10 : 1). **B** Microwave experiments were performed in a CEM Discover reactor set at a maximum temperature of 135 °C (initial power 110 W). [b] Calculated from the ^1H NMR. [c] Using 1 mol% catalyst.

The mechanism of the process as proposed by Oi and Inoue is illustrated in Fig. 2 and closely relates to the mechanism of the corresponding rhodium-catalysed addition of boronic acids described by Hayashi.[2,6] It was noted that the reaction did not occur in the absence of water, suggesting that the active silicon species is likely to be an organosilanetriol **I** generated from the hydrolysis of the organotrialkoxysilane. The organosilanetriol **I**, would then transmetalate with the cationic catalyst **II** to generate the organorhodium intermediate **III** and the side product, SiO_2. Addition of the organorhodium species to substrate **IV** then leads to an η^3-oxa-π-allylrhodium complex **V** that is protonated to afford the product **VI** and the regenerated cationic catalyst. Alternatively, the lack of reactivity in the absence of proton source could be attributed to the η^3-oxa-π-allylrhodium complex **V** being inert to transmetalation which would lead to the catalytic cycle stalling at **V**.

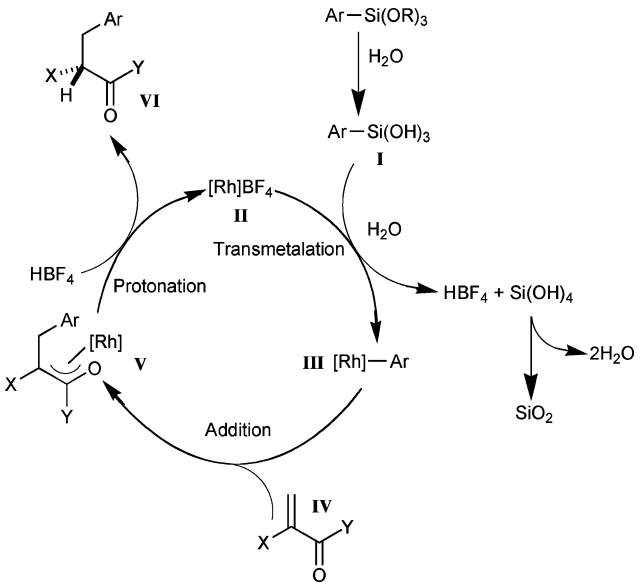
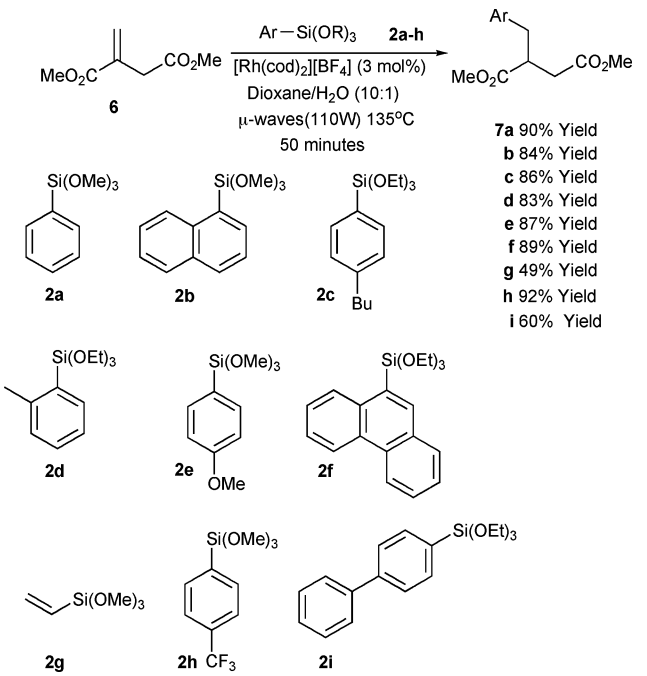


Fig. 2 Mechanism of rhodium-catalysed addition of organotrialkoxysilanes.

To our surprise there was a marked difference in efficiency using the cationic catalysts $[Rh(cod)_2][PF_6]$ and $[Rh(cod)_2][BF_4]$. Whereas the use of $[Rh(cod)_2][BF_4]$ resulted in high conversions to product in short reaction times, the complex with PF_6 counter ion was ineffective and led to protiodesilylation of the organotrialkoxysilane as the predominant reaction pathway along with recovery of starting materials **2a** and **6**. Given that $[Rh(cod)_2][PF_6]$ is an effective catalyst for the conjugate addition of organoboron reagents under identical reaction conditions the organotrialkoxysilane is clearly detrimental to the action of the catalyst.[12] This may be due to the comparatively weak P–F bond being hydrolysed in the presence of the organosilicon reagent whereas the B–F bond in the BF_4 counterion is stable.[13] The partial hydrolysis of PF_6 has been observed previously in transition metal complexes and this process generates HF in the reaction mixture.[14] Interestingly, the addition of a fluoride source to a reaction mixture containing the $[Rh(cod)_2][BF_4]$ catalyst leads to a decrease in the amount of addition product **7a** obtained.[15]

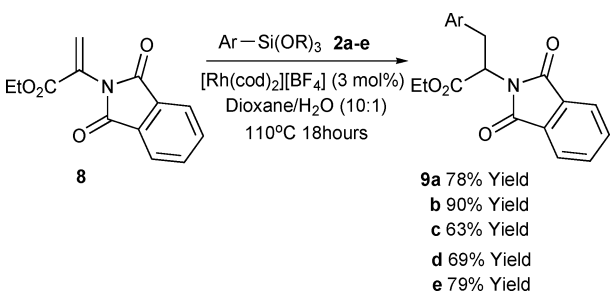
The products from the addition process are of significant utility in the development of pharmaceutical and agrochemical

intermediates.[16] Therefore, the synthesis of a range of 2-substituted succinic esters was performed.[17] For ease of operation and rapid heating, the rhodium-catalysed addition was performed in capped tubes under microwave irradiation. Using the optimal set of reaction conditions, the scope of the organotrialkoxysilane was examined. Pleasingly, in the addition to dimethyl itaconate **6**, the use of sterically and electronically diverse organotrialkoxysilanes (**2a–i**) resulted in excellent conversion and good isolated yields of products **7a–i**. The reaction is tolerant of the substitution pattern and the electronic nature of the siloxane. All the reactions proceeded in similar yields by heating in an oil bath or heating block at 110 °C (Scheme 3).



Scheme 3 The rhodium-catalysed addition of organotrialkoxysilanes.

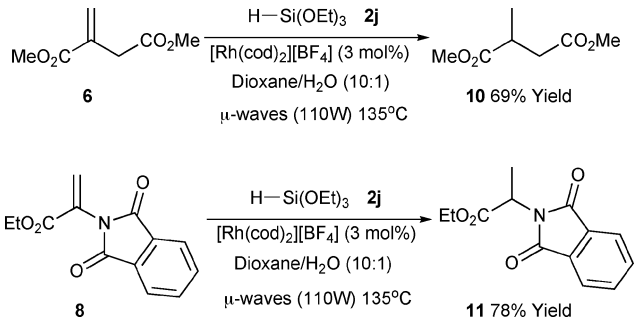
With an efficient protocol established for the addition to dimethyl itaconate **6** our attention turned to the α-phthalimidoacrylic ester derivative **8**.[18] As shown in Scheme 4, the arylation of **8** with selected organotrialkoxysilanes (**2a–e**) was performed by heating in an oil bath at 110 °C for 18 hours. In all cases the reaction proceeded in good yield to provide a useful synthetic approach to unnatural amino acid derivatives **9a–e**. The corresponding reactions carried out under the standard conditions



Scheme 4 The rhodium-catalysed addition to α-phthalimidoacrylic ester derivatives.

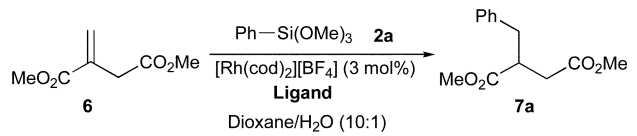
in a microwave reactor provided the products in slightly lower yields reflecting the lower reactivity of this substrate.

The catalytic conjugate addition of hydride is an established process for the reduction of α,β-unsaturated carbonyl derivatives.[19] The transformation employs hydrogen donors such as hydrosilanes or borohydride reagents as an alternative to hydrogen gas. The reduction of α-substituted acrylic esters **6** and **8** with triethoxysilane **2j** occurred under identical conditions to the arylations (Scheme 5). Again, for ease of operation and rapid heating, the reduction was performed in capped tubes under microwave irradiation to afford the products **10** and **11** in good yields.



Scheme 5 The rhodium-catalysed conjugate reduction.

Preliminary investigations into the enantioselective addition of organotrialkoxysilanes to α-substituted acrylic esters focused on the use of (*R*)-BINAP as the chiral ligand (Scheme 6). While carrying out preliminary microwave experiments it was observed that the ligand to metal ratio utilised had a dramatic effect on the outcome of the reaction. Using the catalyst $[Rh(cod)_2][BF_4]$ (3 mol%), in the absence of ligand, at 135 °C, complete conversion of the starting acrylate **6** to product **7a** was observed in 50 minutes (Table 2, entry 1). However upon the addition of (*R*)-BINAP (3 mol%, 1 equivalent) to the reaction, a sharp decrease in reactivity was observed, alongside a moderately low enantiomeric excess of 24% ee (Table 2, entry 2). Upon altering the ligand loading (4.5 mol%, 1.5 equivalents) a 55% conversion and 49% enantiomeric excess was obtained, with higher ligand to rhodium ratios giving no conversion to the desired product (Table 2, entries 3 and 4). The application of sterically-hindered phenols as alternative proton sources impeded the enantioselective reaction as did the addition of fluoride sources such as KF (Table 2, entry 9).



Scheme 6 The enantioselective addition of phenyltrimethoxysilane.

Unfortunately, employing other enantiopure ligands such as the monodentate phosphoramidite (*S*)-MONOPHOS proved unsuccessful (Table 2, entry 6). This is consistent with the previous report of Feringa *et al.* that demonstrated rhodium–phosphoramidite complexes were unable to effect the conjugate

Table 2 Investigation into enantioselectivity[a]

Entry	Ligand	Ligand–[Rh]	ee[b] (%)	Conversion[c] (%)
1	None	—	0	100
2	(*R*)-BINAP	1 : 1	24	70
3	(*R*)-BINAP	3 : 2	49	55
4	(*R*)-BINAP	2 : 1	—	<2
5	(*R*,*R*)-DUPHOS	3 : 2	0	0
6	(*S*)-MONOPHOS	3 : 2	0	0
7	(*R*,*R*)-DIOP	3 : 2	9	100
8	(*R*,*R*)-NORPHOS	3 : 2	0	0
9	(*R*)-BINAP[d]	3 : 2	—	<5

[a] Microwave experiments were performed in a CEM Discover reactor set at a maximum temperature of 135 °C (110 W). [b] Determined by chiral HPLC using a Daicel OD–H column at ambient temperature and a 98 : 2 hexane–IPA solvent system with a flow rate of 1 mL min^{-1}. Two peaks were found at retention times of 19 and 23 minutes, correlating to the two product enantiomers. [c] Calculated from the ^{1}H NMR. [d] Using 2-methoxyphenol as proton source.

addition of organosiloxanes to cyclic enones.[20] Disappointingly, other bidentate phosphorous ligands, such as (*R*,*R*)-DIOP and (*R*,*R*)-DUPHOS did not enhance the enantioselectivity (Table 2, entries 5, 7 and 8). From these results we have established that phosphine ligands retard the conjugate addition of organotrialkoxysilanes to α-substituted acrylic esters and given the modest enantioselectivity observed we elected not to pursue this any further.

In summary, we have demonstrated that the cationic rhodium complex $[Rh(cod)_2][BF_4]$ effectively catalyses the conjugate addition of organotrialkoxysilanes to α-substituted acrylic esters. This methodology is very versatile offering the possibility of obtaining a variety of novel 2-substituted succinate esters and unnatural α-amino acid derivatives, simply by changing the functionality on the starting organosilicon reagent.

Experimental

Commercially available solvents and reagents were obtained from Sigma-Aldrich Company Ltd, Lancaster Synthesis Ltd, Fisher Scientific Ltd and Strem Chemicals UK and were used without further purification. Microwave experiments were performed using a CEM Discover reactor. Solvents and reagents were deoxygenated where necessary by purging with nitrogen. Flash column chromatography was carried out using Merck kieselgel 60 H silica gel (particle size: 0.063–0.100 mm). Melting points were determined using a Büchi 535 melting point apparatus and are uncorrected. Infra red spectra (4000 to 600 cm^{-1}) were recorded on a Perkin Elmer (1600) FT spectrometer with internal calibration. Fast Atom Bombardment (FAB) and Electron Impact (EI) mass spectra were obtained using a Fisons VG Autospec Finnigan MAT 8340 instrument at the University of Bath. Additional mass spectra were run at the EPSRC National Mass Spectrometry Service Centre at Swansea University. High Performance Liquid Chromatography (HPLC) was performed on a Perkin Elmer HPLC-IPM using a Chiralpak OD–H column by Daicel Chemical Ind. Ltd. Elemental analyses were recorded on a Micromass Autospec Spectrometer at the University of Bath.

General procedure for the rhodium-catalysed conjugate addition of organotrialkoxysilanes to α-substituted acrylic esters

A suspension of dimethyl itaconate (0.5 mmol), organotrialkoxysilane (1.25 mmol), and $[Rh(cod)_2][BF_4]$ (0.015 mmol, 3 mol%), in dioxane (1 mL) and water (0.1 mL) was heated in a microwave reactor, under an inert atmosphere, at 135 °C for 50 min (initial power 110 W). The solution was evaporated under reduced pressure and re-dissolved in ethyl acetate (10 mL) and water (10 mL). The phases were separated, and the aqueous phase extracted with ethyl acetate (2 × 10 mL). The combined organics were washed with brine, dried over $MgSO_4$, filtered and concentrated *in vacuo*. The crude material was purified by flash chromatography on silica gel (eluent: petroleum ether–ethyl acetate). Alternatively, the reaction could be carried out by heating in an oil-bath at 110 °C for the indicated time.

Dimethyl 2-benzylsuccinate (7a). Title compound isolated as a colourless oil (106 mg, 90%); R_f (9 : 1, petroleum ether–ethyl acetate) 0.2; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.2–7.1(5H, m, Ar), 3.60 (3H, s, CH_3), 3.57 (3H, s, CH_3), 3.2–3.1 (2H, m, CH_2, CH), 2.7–2.9 (2H, m, CH_2), 2.34 (1H, dd, J = 4.8, 16.8 Hz, CH_2); ^{13}C NMR (75.5 MHz; $CDCl_3$) 175.0, 172.6, 138.5, 129.4, 128.9, 127.4, 52.3, 52.1, 43.4, 38.1, 35.2. Further data were in accordance with previous results in the literature.[21]

Dimethyl 2-((naphthalene-1-yl)methyl)succinate (7b). Title compound isolated as a white solid (120 mg, 84%), mp 96 °C (lit.[22] 95.7 °C); R_f (9 : 1, petroleum ether–ethyl acetate) 0.16; IR (nujol, cm^{-1}) ν 1719 (C=O), 1050 (C–O); ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.02 (1H, d, J = 8.7 Hz, Ar), 7.80 (1H, d, J = 9.3 Hz, Ar), 7.69 (1H, d, J = 8.4 Hz, Ar), 7.46 (2H, m, Ar), 7.32 (1H, t, J = 6.9 Hz, Ar), 7.21 (1H, d, J = 8.1 Hz, Ar), 3.61 (3H, s, OCH_3), 3.4–3.5(4H, m, CH_2, OCH_3), 3.24 (1H, m, CH), 3.06 (1H, dd, J = 9.3, 13.5 Hz, CH_2), 2.69 (1H, dd, J = 9.3, 17.1 Hz, CH_2), 2.37 (1H, dd, J = 5.1, 17.1 Hz, CH_2); ^{13}C NMR (75.5 MHz; $CDCl_3$) 172.6, 175.3, 134.6, 134.4, 132.1, 129.3, 128.1, 127.8, 126.7, 126.1, 125.7, 123.9, 52.4, 52.1, 42.5, 35.6, 35.5. Further data were in accordance with previous results in the literature.[21]

Dimethyl 2-(4-butylbenzyl)succinate (7c). Title compound isolated as a colourless oil (126 mg, 86%); R_f (9 : 1, petroleum ether–ethyl acetate) 0.19; IR (film, cm^{-1}) ν 3459, 2858, 1740, 1614, 1594, 1515, 1437, 1356, 1331, 1264, 1202, 1168, 837; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.0–7.05 (2H, d, J = 8.2 Hz, Ar), 6.97 (2H, d, J = 8.1 Hz, Ar), 3.59 (3H, s, CH_3), 3.54 (3H, s, CH_3), 3.1–2.9 (2H, m, $CH2$, CH), 2.7–2.9 (2H, m, CH_2), 2.5 (2H, m, CH_2), 2.3 (1H, dd, J = 4.7, 16.7 Hz, $CH2$), 1.5 (2H, m, CH_2), 1.25 (2H, m, CH_2), 0.85 (3H, t, J = 7.3, CH_3); ^{13}C NMR (75.5 MHz; $CDCl_3$) 175.2, 172.7, 144.70, 135.5, 134.9, 129.7, 129.2, 128.97, 52.3, 52.1, 43.4, 37.7, 35.6, 34.3, 34.0, 22.6, 14.3; HRMS (EI^+) $[MH^+]$ calcd for $C_{17}H_{24}O_4$, m/z 293.1747; found m/z 293.1744; elemental analysis calcd (%) for $C_{17}H_{24}O_4$: C 69.8, H 8.3, N 0; found: C 70.1, H 8.4, N 0%.

Dimethyl 2-(2-methylbenzyl)succinate (7d). Title compound isolated as a colourless oil (104 mg, 83%); R_f (9 : 1, petroleum ether–ethyl acetate) 0.2; IR (film, cm^{-1}) ν 2953, 1736, 1638, 1605, 1437, 1353, 1264, 1206, 1162, 1006; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.1–7.0 (4H, m, Ar), 3.60 (3H, s, CH_3), 3.57 (3H, s, CH_3), 3.2–3.1 (2H, m, CH_2, CH), 2.7–2.6 (2H, m, CH_2), 2.34 (1H, dd, J = 4.8, 16.8 Hz, CH_2), 2.2 (3H, s, CH_3); ^{13}C NMR (75.5 MHz; $CDCl_3$)

175.3, 172.6, 136.7, 130.9, 130.2, 127.2, 126.3, 52.3, 52.1, 42.1, 35.6, 35.4, 19.6; HRMS (EI$^+$) [MH$^+$]; calcd for $C_{14}H_{18}O_4$, m/z 251.1278; found m/z 251.1282.

Dimethyl 2-(4-methoxybenzyl)succinate (7e). Title compound isolated as a colourless oil (116 mg, 87%); R_f (9 : 1, petroleum ether–ethyl acetate) 0.18; IR (film, cm^{-1}) ν 2953, 1732 (C=O); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.0 (2H, d, J = 8.7 Hz, Ar), 6.76 (2H, d, J = 8.7 Hz, Ar), 3.72 (3H, s, ArOCH_3), 3.60 (3H, s, CH_3), 3.57 (3H, s, CH_3), 2.8–3.1 (2H, m, CH_2, CH), 2.5–2.7 (2H, m, CH_2), 2.33 (1H, dd, J = 5.1, 16.8 Hz, CH_2). Further data were in accordance with previous results in the literature.[21]

Dimethyl 2-((phenanthren-10-yl)methyl)succinate (7f). Title compound isolated as a white solid (150 mg, 89%), mp 94–97 °C; R_f (9 : 1, petroleum ether–ethyl acetate) 0.15; IR ($CDCl_3$, cm^{-1}) ν 2923, 2726, 2671, 1719, 1460, 1377, 1305, 1151, 1076; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.7–8.6 (1H, m, Ar), 8.55 (1H, d, J = 8.0 Hz, Ar), 8.1–8.2 (1H, m, Ar), 7.75 (1H, dd, J = 1.3, 7.4 Hz, Ar), 7.7–7.4 (5H, m, Ar), 3.65 (3H, s, CH_3), 3.5–3.6 (1H, m, CH_2), 3.5 (3H, s, CH_3), 3.25–3.4 (1H, m, CH), 3.1–3.2 (1H, m, CH_2), 2.7 (1H, dd, J = 9.8, 7.8 Hz, CH_2), 2.4 (1H, dd, J = 4.5, 11.9 Hz, CH_2); ^{13}C NMR (75.5 MHz; $CDCl_3$) 175.3, 172.6, 132.8, 131.8, 131.2, 131.1, 130.4, 128.6, 128.4, 127.3, 127.1, 126.8, 124.6, 123.7, 122.8, 52.4, 52.1, 42.0, 36.1, 35.6; HRMS (EI$^+$) [MH$^+$]; calcd for $C_{21}H_{20}O_4$, m/z 337.1434, found 337.1438.

Dimethyl 2-allylsuccinate (7g). Title compound isolated as a colourless oil (46 mg, 49%); R_f (9 : 1, petroleum ether–ethyl acetate) 0.19; ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.6–5.7 (1H, m, CH), 5.05 (1H, d, J = 4.29 Hz, CH), 4.95 (1H, s, CH), 3.60 (3H, s, CH_3), 3.58 (3H, s, CH_3), 3.0–2.9 (1H, m, CH), 2.65 (1H, dd, J = 9.08, 7.63 Hz, CH_2), 2.34 (2H, m, CH_2), 2.2 (1H, m, CH). Further data were in accordance with previous results in the literature.[21]

Dimethyl 2-(4-(trifluoromethyl)benzyl)succinate (7h). Title compound isolated as a colourless oil (140 mg, 92%); R_f (4 : 1, petroleum ether–ethyl acetate) 0.37; IR (film, cm^{-1}) ν 2955, 2259, 1925, 1732, 1619, 1585, 1548, 1438, 1418, 1324; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.47 (2H, d, J = 8.2 Hz, Ar), 7.2 (2H, d, J = 7.9 Hz, Ar), 3.58 (3H, s, CH_3), 3.57 (3H, s, CH_3), 3.05–3.11 (2H, m, CH_2, CH), 2.78 (1H, dd, J = 7.15, 13.1 Hz, CH_2), 2.6 (1H, dd, J = 8.2, 16.5 Hz, CH_2), 2.34 (1H, dd, J = 5.2, 16.5 Hz, CH_2); ^{13}C NMR (75.5 MHz, $CDCl_3$) 173.1, 170.9, 141.4, 127.8, 124.9, 121.3, 117.7, 50.9, 50.8, 41.7, 36.3, 33.9; HRMS (EI$^+$) [MNH$_4^+$]; calcd for $C_{14}H_{15}O_4F_3{\cdot}NH_4$ m/z 322.1261, found 322.1260.

Dimethyl 2-(4-(biphenyl)benzyl)succinate (7i). Title compound isolated as a white solid (93 mg, 60%); mp 61–65 °C; R_f (4 : 1, petroleum ether–ethyl acetate) 0.3; IR (KBr, cm^{-1}) ν 3027 (C–H), 3005 (C–H), 2954 (C–H), 2926 (C–H), 1761 (C=O), 1726 (C=O), 1175 (C–O), 1153 (C–O); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.42–7.50 (4H, m, Ar), 7.3–7.38 (2H, m, Ar), 7.2–7.28 (1H, m, Ar), 7.14–7.16 (2H, m, Ar), 3.6 (3H, s, CH_3), 3.56 (3H, s, CH_3), 2.98–3.12 (2H, m, CH_2, CH), 2.68–2.76 (1H, dd, J = 8.2, 13.1 Hz, CH_2), 2.58–2.67 (1H, dd, J = 8.6, 16.1 Hz, CH_2), 2.32–2.4 (1H, dd, J = 4.8, 16.5 Hz, CH_2); ^{13}C NMR (75.5 MHz, $CDCl_3$) 175.1, 172.7, 141.1, 140.0, 137.6, 129.8, 129.2, 127.6, 127.4, 127.0, 52.5, 52.4, 43.4, 37.7, 35.3; HRMS (EI$^+$) [MNH$_4^+$]; calcd for $C_{19}H_{20}O_4{\cdot}NH_4$ m/z 330.1700, found 330.1700.

General procedure for the rhodium-catalysed conjugate addition of organotrialkoxysilanes to α-amino acrylates

A suspension of ethyl-α-phthalimidoacrylate (0.5 mmol), organotrialkoxysilane (1.25 mmol), and [Rh(cod)$_2$][BF$_4$] (0.015 mmol, 3 mol%), in dioxane (2 mL) and water (0.2 mL) was refluxed under an inert atmosphere. After 24 hours the solution was evaporated under reduced pressure and re-dissolved in ethyl acetate (10 mL) and water (10 mL). The phases were separated, and the aqueous phase extracted with ethyl acetate (2 × 10 mL). The combined organics were washed with brine, dried over $MgSO_4$, filtered and concentrated *in vacuo*. The crude material was purified by flash chromatography on silica gel (eluent: petroleum ether–ethyl acetate).

Ethyl 2-(1,3-dioxoisoindolin-2-yl)-3-phenylpropanoate (9a). Title compound isolated as a white solid (126 mg, 78%); R_f (4 : 1, petroleum ether–ethyl acetate) 0.42; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.74–7.79 (2H, m, *Ar*), 7.66–7.70 (2H, m, *Ar*), 7.12–7.20 (5H, m, Ph), 5.14 (1H, dd, J = 5.3, 10.9, NCH), 4.25 (2H, dq, J = 1.6, 7.2, CH_2CH_3), 3.49–3.64 (2H, m, CH_2Ph), 1.26 (3H, t, J = 7.2, CH_3). Further data were in accordance with previous results in the literature.[18]

Ethyl 3-(naphthalen-1-yl)-2-(1,3-dioxoisoindolin-2-yl) propanoate (9b). Title compound isolated as a white solid (168 mg, 90%); mp 233–234 °C; R_f (4 : 1, petroleum ether–ethyl acetate) 0.38; mp 87–90 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.10 (1H, d, J = 8.7, Ar), 7.81 (1H, d, J = 8.7 Hz, Ar), 7.72–7.76 (2H, m, Ar), 7.65–7.69 (3H, m, Ar), 7.43–7.51 (2H, m, Ar), 7.22–7.26 (2H, m, Ar), 5.31 (1H, dd, J = 4.5, 11.3 Hz), 4.3 (2H, dq, J = 1.1, 7.2), 4.17 (1H, dd, J = 4.5, 14.7 Hz), 3.9 (1H, dd, J = 11.3, 14.7), 1.28 (3H, t, J = 7.2 Hz); ^{13}C NMR (75.5 MHz, $CDCl_3$) 167.7, 166.2, 132.8, 132.6, 131.7, 130.5, 130.3, 127.7, 126.6, 126.0, 125.2, 124.5, 124.0, 122.2, 121.8, 60.9, 51.6, 30.6, 12.9. Further data were in accordance with previous results in the literature.[18]

Ethyl 3-(4-butylphenyl)-2-(1,3-dioxoisoindolin-2-yl) propanoate (9c). Title compound isolated as a colourless oil (120 mg, 63%); R_f (4 : 1, petroleum ether–ethyl acetate) 0.41; IR (film, cm^{-1}) ν 2930, 1778, 1744 (C=O), 1719, 1614, 1515, 1467, 1445, 1388, 1243; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.6–7.7 (4H, m, Ar), 6.98 (2H, d, J = 8.08 Hz, Ar), 6.9 (2H, d, J = 8.08 Hz, Ar), 5.06 (1H, dd, J = 5.6, 10.89, NCH), 4.16 (2H, dq, J = 1.7, 7.1 Hz, CH_2CH$_3$), 3.38–3.54 (2H, m, CHCH_2), 2.41 (2H, t, J = 7.56 Hz, CH_2), 1.35–1.45 (2H, m, CH$_2$), 1.1–1.2 (5H, m, CH_3CH$_2$), 0.8 (3H, t, J = 7.27, CH$_3$); ^{13}C NMR (75.5 MHz, $CDCl_3$) 169.3, 167.9, 141.7, 134.5, 134.4, 134.2, 132.0, 129.0, 128.9, 123.7, 62.3, 53.9, 35.5, 34.6, 33.8, 22.6, 14.5, 14.3; HRMS (EI$^+$) [MH$^+$]; calcd for $C_{23}H_{25}NO_4$, m/z 380.1856, found 380.1856.

Ethyl 2-(1,3-dioxoisoindolin-2-yl)-3-*o*-tolylpropanoate (9d). Title compound isolated as a colourless oil (116 mg, 69%); R_f (4 : 1, petroleum ether–ethyl acetate) 0.35; IR (film, cm^{-1}) ν 2981, 1777, 1743, 1715, 1631, 1494, 1467, 1423, 1388; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.74–7.79 (2H, m, Ar), 7.66–7.70 (2H, m, Ar), 6.9–7.1 (4H, m, Ph), 5.09 (1H, dd, J = 5.3, 10.9, NCH), 4.1 (2H, dq, J = 1.9, 7.2, CH_2CH$_3$), 3.4–3.64 (2H, m, CH_2Ph), 2.3 (3H, s, Ar–Me), 1.26 (3H, t, J = 7.2, CH_3), ^{13}C NMR (75.5 MHz, $CDCl_3$) 169.4, 167.9, 136.9, 135.2, 134.5, 131.9, 130.9, 130.0, 127.4, 126.3, 123.8,

120.70, 62.4, 52.1, 32.7, 19.6, 14.5; HRMS (EI+) [MH^+]; calcd for $C_{20}H_{19}NO_4$, m/z 338.1387, found 338.1381.

Ethyl 3-(4-methoxyphenyl)-2-(1,3-dioxoisoindolin-2-yl)propanoate (9e). Title compound isolated as a colourless oil (140 mg, 79%); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.75–7.81 (2H, m, Ar), 7.65–7.72 (2H, m, Ar), 7.07 (2H, d, $J = 8.7$ Hz, 2,6-Ar–CH), 6.71 (2H, d, $J = 8.7$ Hz, 3,5-Ar–CH), 5.09 (1H, dd, $J = 5.6$, 10.7 Hz, NCH), 4.25 (2H, dq, $J = 1.9$, 7.2 Hz, CH_2CH_3), 3.70 (3H, s, OMe), 3.43–3.58 (2H, m, $CHCH_2$), 1.26 (3H, t, J 7.2 Hz, CH_3). Further data were in accordance with previous results in the literature.[18]

General procedure for the rhodium-catalysed conjugate addition of triethoxysilane

A suspension of α-substituted acrylic ester (0.5 mmol), triethoxysilane (205 mg, 1.25 mmol), and $[Rh(cod)_2][BF_4]$ (0.015 mmol, 3 mol%), in dioxane (1 mL) and water (0.1 mL) was heated in a microwave reactor, under an inert atmosphere, at 135 °C for 50 min (initial power 110 W). The solution was evaporated under reduced pressure and re-dissolved in ethyl acetate (10 mL) and water (10 mL). The phases were separated, and the aqueous phase extracted with ethyl acetate (2 × 10 mL). The combined organics were washed with brine, dried over $MgSO_4$, filtered and concentrated *in vacuo.* The crude material was purified by flash chromatography on silica gel (eluent: petroleum ether–ethyl acetate).

Dimethyl 2-methylsuccinate (10). Title compound isolated as a colourless oil (57 mg, 71%); R_f (9 : 1, petroleum ether–ethyl acetate) 0.19; IR (film, cm^{-1}) ν 3425, 1734 (C=O); ^{1}H NMR (300 MHz, $CDCl_3$) δ 3.63 (3H, s, CH_3), 3.61 (3H, s, CH_3), 2.82–2.92 (1H, m, CH), 2.7 (1H, dd, $J = 8.06$, 8.40, CH_2), 2.35 (1H, dd, $J = 6.07$, 10.4, CH_2), 1.12 (3H, d, $J = 7.1$, CH_3); ^{13}C NMR (75.5 MHz, $CDCl_3$) 176.1, 172.7, 52.5, 52.4, 37.9, 36.0, 17.4; MS (EI+) [MH^+]; calcd for $C_7H_{12}O_4$, m/z 160.0730, found 160.0302.

Ethyl 2-(1,3-dioxoisoindolin-2-yl)propanoate (11). Title compound isolated as a white solid, alongside trace amounts of inseparable ethyl-α-phthalimidoacrylate; R_f (4 : 1, petroleum ether–ethyl acetate) 0.41; IR (nujol, cm^{-1}) ν 2922, 2853, 1783, 1716, 1611, 1464, 1385, 1303, 1262, 1233, 1201, 1152, 1099, 1082, 1064, 1021, 1008, 934, 883, 799, 761, 719; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.87 (2H, dd, $J = 3.0$, 5.3 Hz, Ar), 7.74 (2H, dd, $J = 3.0$, 5.3 Hz, Ar), 4.97 (1H, q, $J = 7.2$ Hz, CH), 4.21 (2H, dq, $J = 1.3$, 7.2 Hz, CH_2), 1.70 (3H, d, $J = 7.2$ Hz, $CHCH_3$), 1.24 (3H, t, $J = 7.2$ Hz, CH_2CH_3); ^{13}C NMR (75.5 MHz, $CDCl_3$) 170.1, 167.8, 134.5, 132.3, 123.9, 62.2, 48.0, 15.7, 14.5.

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