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Palladium-catalyzed desulfinylative C–C allylation of Grignard reagents and enolates using allylsulfonyl chlorides and esters

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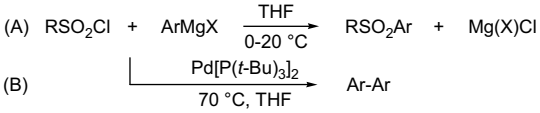
ABSTRACT

2-Methylprop-2-ene-, prop-2-ene-, 1-methylprop-2-ene-, and (*E*)-but-2-enesulfonyl chlorides have been used as electrophilic partners in desulfinylative palladium-catalyzed C–C coupling with Grignard reagents and sodium salts of dimethyl malonate and methyl acetoacetate. Neopentyl alk-2-ene sulfonates can also be used as electrophilic partners in desulfinylative allylic arylations and allylic alkylations. The regioselectivity of the allylic arylation and alkylation depends on the nature of the catalyst. With $PdCl_2(PhCN)_2$, (*E*)-crotyl derivatives are formed in high regioselectivity using either 1-methylprop-2-ene- or (*E*)-but-2-enesulfonyl chloride.

1. Introduction

The search of efficient methods for the construction of carbon–carbon bonds represents an ongoing, central theme of research of organic synthesis.[1–11] Transition metal catalyzed cross-coupling of organometallic reagents with halides or triflates constitutes today one of the most powerful methods to generate carbon–carbon bonds.[12–17] Arene- and alkanesulfonyl chlorides are inexpensive and readily available compounds. They have been used for more than a century in material sciences and medicinal chemistry.[18–23] Recently, we have shown that Stille, carbonylative Stille,[24,25] Suzuki–Miyaura,[26] Sonogashira–Hagihara[27] type cross-couplings and Mizoroki–Heck[28,29] type arylations can be carried out using sulfonyl chlorides as electrophilic partners under desulfinylation conditions.[30] In the case of Mizoroki–Heck coupling reaction, Pd nanoparticles in nitrile-functionalized ionic liquid, without expensive or toxic ligands can be used as recoverable catalyst.[29] We have also shown that aliphatic sulfonyl chlorides are also excellent electrophiles.[31] Among the earliest, most economical and useful nucleophilic partners are the Grignard reagents, which can be coupled with all kinds of electrophilic partners such as sulfides,[32–39] sulfoxides[32,40] sulfoximines,[41–45] sulfones,[46–52] sulfonic esters,[53–55] and sulfonamides[56] in the presence of nickel catalysts. Since 1929 it is known that Grignard reagents displace sulfonyl chlorides to generate the corresponding sulfones (Scheme 1A).[57] Early experiments with sulfonyl chlorides and aryl Grignard reagents in the presence of $Pd[P(t\text{-}Bu)_3]_2$ catalyst led to products of aryl–aryl homocoupling, the organomagnesium reagents had to be converted into organozinc reagents for successful desulfinylative C–C cross-coupling reactions (Scheme 1B).[58]



Scheme 1. Sulfones synthesis and Grignard reagent C–C homocoupling.

We have now examined the palladium-catalyzed desulfinylative C–C cross-coupling reaction using alk-2-ene-sulfonyl chlorides and neopentyl alk-2-ene sulfonic esters with Grignard reagents ('hard nucleophiles') and sodium β-oxoenolates ('soft nucleophiles').

2. Results and discussion

One-pot syntheses of alk-2-enesulfonyl chlorides **2a–c** and alk-2-enesulfonic esters **3a–c** were realized applying the ene-reaction of SO_2[59] with allylsilanes **1a–c** (Scheme 2A).[60–64] Neopentyl

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(*E*)-crotylsulfonate (**3d**) was prepared from (*E*)-crotylsulfonyl chloride (**2d**) as shown in Scheme 2B.[65]

Our exploratory experiments engaged first sulfonyl chlorides **2a** and **2b** and various Grignard reagents, PhZnCl, sodium salts of methyl acetoacetate and dimethyl malonate as nucleophiles. Our results are summarized in Tables 1 and 2.

Crucial for the success was the slow addition of the nucleophilic reagent to a premixed THF solution of the sulfonyl chloride with the palladium catalyst. The formation of sulfones can be completely suppressed by the dropwise addition of Grignard reagent. Temperature can be varied between 20 °C and 78 °C without affecting yield in products of allylation **4** significantly (Table 1, compare entries 1 and 2 and entries 7 and 8). Using 2-methylprop-2-enesulfonyl chloride (**2a**), allylation of aryl and alkyl Grignard reagents have been successful, although alkyl Grignard reagents showed slower reactions (entries 5–7) than aryl derivatives (entries 1–4). With PhZnCl and **2a**, coupling occurs also but was significantly slower than with PhMgCl (entry 8). With **2b**, coupling with *o*-tolylMgCl and *p*-methoxyphenylMgBr were faster and better yielded (Table 2, entries 9–10) than the reaction with *n*-octylMgBr (entry 11), which provided undec-1-ene in 66% yield. In all cases Pd[P(*t*-Bu)$_3$]$_2$ in 5 mol % and THF led to better reaction rates and yields than other palladium catalysts as illustrated with **2a** and **2b** and Grignard reagents (Tables 1 and 2). But in the case of soft nucleophiles, Pd(PPh$_3$)$_4$ was found to be better catalyst (Table 2, entries 12 and 15) than Pd[P(*t*-Bu)$_3$]$_2$ (entry 13). The sodium salt of methyl acetoacetate has also been allylated successfully (entries 14 and 16).

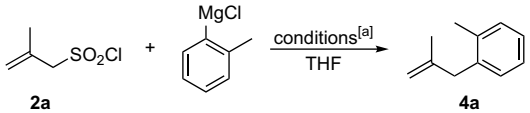
We then explored whether 2-methylprop-2-enesulfonic ester **3a** would also be suitable for the desulfinylative C–C coupling with Grignard reagents. For that neopentyl ester **3a** was reacted with *o*-tolylMgCl in the presence of various catalysts (5 mol %) in boiling THF. Our results are summarized in Table 3.

The fastest and best yielded (72%) reaction used Pd(PPh$_3$)$_4$ as catalyst (Table 3, entry 1). With NiCl$_2$(dppf) the yield was slightly lower (68%) and with [Ir(COD)Cl]$_2$, the reaction did not occur. Interestingly, Fe(acac)$_3$ is also able to catalyze the desulfinylative coupling (Table 3, entry 3) provided that it is reacted first with 10 mol % of the Grignard reagents, followed by the addition of **3a** and slow addition of an excess (1.5–2 fold) of the Grignard reagent.

With these successes in hand we then explored whether our conditions could be applied to the regioselective crotylation of metallic nucleophiles. Our results are summarized in Table 4 for the reactions of (*E*)-crotylsulfonyl chloride (**2d**) and *o*-tolylMgCl using various palladium and nickel catalysts. Yields were not measured in all our assays, but judging from the ^{1}H NMR spectra of the crude reaction mixtures, they were all better than 50%. In all cases the linear product **5a** was favored (product of no allylic rearrangement). The regioselectivity (product ratio **5a**/**6a**) was the best (96:4, yield 52%) using Pd$_2$(dba)$_3$ and xantphos ligand[66–71] (entry 6). The best regioselectivity (95:5) and yield (75%) were realized using PdCl$_2$(PhCN)$_2$ as catalyst, for a reaction in THF at room temperature (entry 16). As for the desulfinylative methallylation (Table 1), Pd[P(*t*-Bu)$_3$]$_2$ led to the fastest reaction and highest yield (78%), but with a lower regioselectivity (entry 8).

Application of Hermann's palladacycle[72,73] (entry 14) did not lead to any significant improvement of the regioselectivity. In the

Table 1
Study of the effect of palladium catalysts on the reactivity of Grignard reagents with sulfonyl chloride **2b**

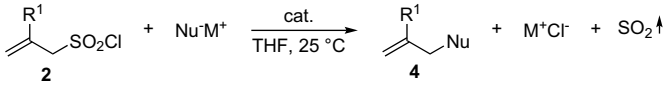


2a **4a**

Entry	Conditions[a]	Reaction time	Yield[b]
1	Pd(PPh$_3$)$_4$, 78 °C	2 h	51%
2	Pd(PPh$_3$)$_4$, 25 °C	2–3 h	55%
3	PdCl$_2$(dppf), 25 °C	2–3 h	39%
4	Pd$_2$(dba)$_3$, 25 °C	1 h	80%
5	Pd(PhCN)$_2$Cl$_2$, 25 °C	1 h	78%
6	PdCl$_2$(PPh$_3$)$_2$, 25 °C	2–3 h	48%
7	Pd[P(*t*-Bu)$_3$]$_2$, 25 °C	0.5 h	87%
8	Pd[P(*t*-Bu)$_3$]$_2$, 78 °C	0.5 h	85%

[a] The reaction of sulfonyl chloride (0.65 mmol) with Grignard reagent (1 mmol) was made in THF (4 mL) in the presence of palladium catalyst (0.033 mmol).
[b] Yield determined after flash chromatography. THF=tetrahydrofuran, dppf=1,1′-bis(diphenylphosphino)ferrocene, dba=dibenzylideneacetone.

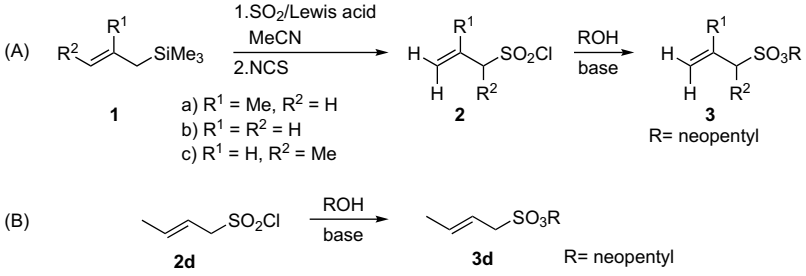
Table 2
Allylic alkylation and arylation using 2-methylprop-2-ene-sulfonyl chloride (**2a**) and prop-2-enesulfonyl chloride (**2b**) and various nucleophiles giving products of desulfinylative C–C cross-coupling **4**



2 **4**

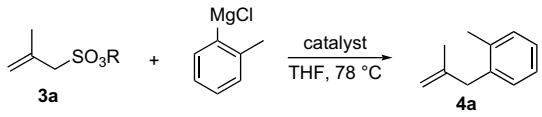
Entry		NuM	Cat. (5 mol %)	Time	Product (yield)[a]
1	**2a**	*o*-tolylMgCl	Pd[P(*t*-Bu)$_3$]$_2$	0.5 h	**4a** (87%)
2	**2a**	PhMgCl	Pd[P(*t*-Bu)$_3$]$_2$	0.5 h	**4b** (82%)
3	**2a**	*m*-tolylMgCl	Pd[P(*t*-Bu)$_3$]$_2$	0.5 h	**4c** (62%)
4	**2a**	*p*-MeOC$_6$H$_4$MgBr	Pd[P(*t*-Bu)$_3$]$_2$	0.5 h	**4d** (79%)
5	**2a**	BnMgCl	Pd[P(*t*-Bu)$_3$]$_2$	0.5 h	**4e** (75%)
6	**2a**	PhCH$_2$CH$_2$MgCl	Pd[P(*t*-Bu)$_3$]$_2$	6 h	**4f** (62%)[b]
7	**2a**	*n*-BuMgCl	Pd[P(*t*-Bu)$_3$]$_2$	1 h	**4g** (28%)[c]
8	**2a**	PhZnCl	Pd[P(*t*-Bu)$_3$]$_2$	6 h	**4b** (57%)
9	**2b**	*o*-tolylMgCl	Pd[P(*t*-Bu)$_3$]$_2$	0.5 h	**4h** (76%)
10	**2b**	*p*-MeOC$_6$H$_4$MgBr	Pd[P(*t*-Bu)$_3$]$_2$	0.5 h	**4i** (85%)
11	**2b**	*n*-octylMgBr	Pd[P(*t*-Bu)$_3$]$_2$	3 h	**4j** (66%)
12	**2a**	MeOOC–CH=C(OMe)ONa	Pd(PPh$_3$)$_4$	0.5 h	**4k** (76%)
13	**2a**	MeOOC–CH=C(OMe)ONa	Pd[P(*t*-Bu)$_3$]$_2$	0.5 h	**4k** (48%)
14	**2a**	MeOOC–CH=C(Me)ONa	Pd(PPh$_3$)$_4$	0.5 h	**4l** (78%)
15	**2b**	MeOOC–CH=C(OMe)ONa	Pd(PPh$_3$)$_4$	0.5 h	**4m** (92%)
16	**2b**	MeOOC–CH=C(Me)ONa	Pd(PPh$_3$)$_4$	0.5 h	**4n** (89%)

[a] Yield determined after flash chromatography purification.
[b] 2.5 equiv. of Grignard reagent necessary.
[c] Microwave heating for 1 h.



Scheme 2. Syntheses of alk-2-enesulfonyl chlorides and neopentyl alk-2-enesulfonates.

Table 3
Effect of the transition metal catalyst on the cross-coupling of neopentyl 2-methylprop-2-enesulfonate (**3a**) with *o*-tolylMgCl



Entry	Catalyst (equiv)	Reaction time	Yield[a]
1	$Pd(PPh_3)_4$ (5 mol %)	2 h	72%
2	$NiCl_2(dppf)$ (5 mol %)	3 h	68%
3	$Fe(acac)_3$ (5 mol %)	21 h	65%
4	$[Ir(COD)Cl]_2$ (5 mol %)	2 h	0%[b]

Conditions: the reaction of sulfonic ester (1 mmol) with Grignard reagent (1.5–2.5 mmol) was made in refluxing THF (5 mL) with catalyst (0.05 mmol).
[a] Yield of the coupled product was determined after flash chromatography.
[b] No coupling product but the corresponding sulfone was formed.

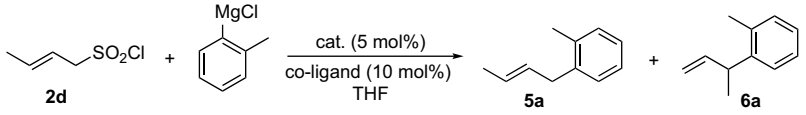
presence of Buchwald's ligand **L2**,[74–76] Trost's ligand **L3**,[77–83] or triarylphosphite ligand **L4**[84,85] no further improvement could be observed.

We then applied our best conditions found for the desulfinylative crotylation reported in Table 4 to the reaction of 1-methylprop-2-enesulfonyl chloride (**2c**) and various nucleophiles. Our results are summarized in Table 5, together with those obtained for the reactions of **2d** with further nucleophiles.

Except for the $Pd(PPh_3)_4$-catalyzed reactions of *m*-tolylMgCl with either the branched (**2c**) or linear sulfonyl chloride (**2d**) that both led to a 1:1 mixture of **5b**+**6b** in mediocre yields (Table 5, entries 3 and 6), the major products of desulfinylative C–C cross-coupling are the linear (*E*)-crotyl derivatives **5**.

As for reaction of **2d** with *o*-tolylMgCl (Table 4, entry 16) the best regioselectivity and yield were obtained with $PdCl_2(PhCN)_2$ as catalyst (Table 5, entries 1, 2, 4, 5). Using $Pd(PPh_3)_4$ catalysts that gave the best yielded reactions **2a**, **2b** with sodium enolates, the regioselectivity (**5** vs **6**) remained bad for the desulfinylative allylations of the sodium salts of dimethyl malonate (entries 7 and 9) and of methyl acetoacetate (entries 8 and 10) with **2c** and **2d**. These results suggest that the mechanism of C–C bond formation in these reactions involves the formation of (π-allyl)(ligand)palladium intermediates that are attacked then by the nucleophiles. This

Table 4
Regioselectivity of the desulfinylative crotylation of *o*-tolylMgCl with (*E*)-crotylSO_2Cl (**2d**) giving the linear and branched products **5a** and **6a**



Entry	Catalyst	Co-ligand	Temperature	Regioselectivity **5a**/**6a**[a] (yield[b])
1	$NiCl_2(dppf)$	—	25 °C	81/19
2	$Pd(PPh_3)_4$	—	25 °C	74/16
3	$Pd_2(dba)_3$	DPPF	25 °C	79/21
4	$Pd_2(dba)_3$	DPPP	25 °C	75/25[c]
5	$Pd_2(dba)_3$	BINAP	25 °C	90/10
6	$Pd_2(dba)_3$	**L1**	25 °C	96/4 (52%)
7	$Pd_2(dba)_3$	PCy_3	25 °C	—[d]
8	$Pd[P(t\text{-}Bu)_3]_2$	—	25 °C	77/23 (78%)
9	$Pd[P(t\text{-}Bu)_3]_2$	—	80 °C	93/7
10	$Pd[P(t\text{-}Bu)_3]_2$	—	0 °C	78/22
11	$(\pi\text{-allylPdCl})_2$	—	25 °C	72/18
12	$Pd_2(dba)_3$	**L2**	25 °C	89/11
13	$Pd_2(dba)_3$	**L3**	25 °C	88/12
14	Palladacycle	—	25 °C	90/10
15	$Pd_2(dba)_3$	**L4**	25 °C	89/11
16	$PdCl_2(PhCN)_2$	—	25 °C	95/5 (75%)

Conditions: 0.65 mmol of **2d** and 1 mol of Grignard reagent in THF (4 mL).
[a] Selectivity was determined by ^1H NMR of the crude reaction.
[b] Yield of **5a**+**6a** determined after flash chromatography.
[c] Coupling product was observed only in trace amount.
[d] Gave a complex mixture of products. DPPF=1,1′-bis(diphenylphosphino)ferrocene, DPPP=1,3-bis(diphenylphosphino)propane, BINAP=2,2′-bis(diphenylphosphino)-1,1′-binaphthyl.

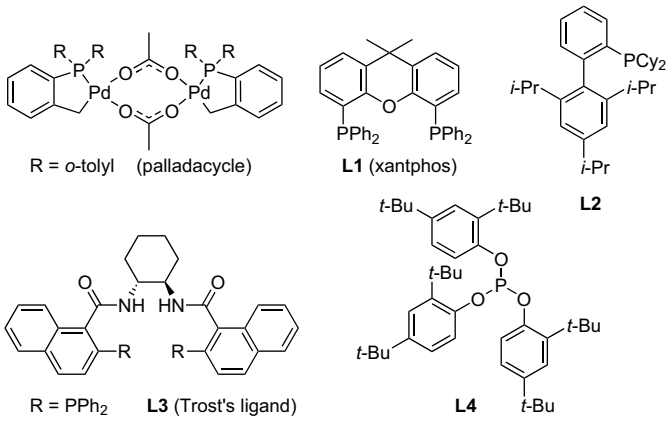
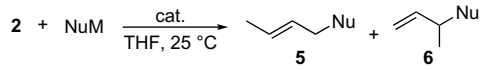


Table 5
Desulfinylative crotylation of metallic nucleophiles (NuM) using sulfonyl chlorides **2c** and **2d**

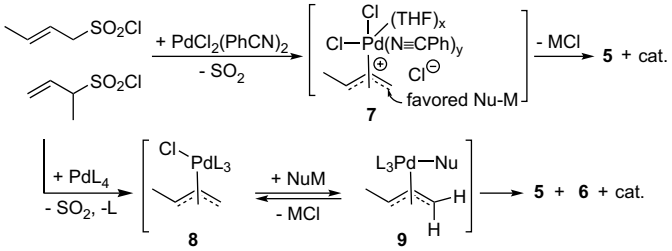


Entry		NuM	Catalyst (5 mol %)	Products (yield)[a]	Regioselectivity **7**/**8**[b]
1	**2c**	*o*-tolylMgCl	$PdCl_2(PhCN)_2$	**5a**+**6a** (69%)	95/5
2	**2c**	*m*-tolylMgCl	$PdCl_2(PhCN)_2$	**5b**+**6b** (56%)	96/4
3	**2c**	*m*-tolylMgCl	$Pd(PPh_3)_4$	**5b**+**6b** (42%)	50/50[c]
4	**2d**	*o*-tolylMgCl	$PdCl_2(PhCN)_2$	**5a**+**6a** (75%)	95/5
5	**2d**	*m*-tolylMgCl	$PdCl_2(PhCN)_2$	**5b**+**6b** (68%)	93/7
6	**2d**	*m*-tolylMgCl	$Pd(PPh_3)_4$	**5b**+**6b** (48%)	50/50[c]
7	**2c**	MeOOC–CH=C(OMe)ONa	$Pd(PPh_3)_4$	**5c**+**6c** (76%)	52/48
8	**2c**	MeOOC–CH=C(Me)ONa	$Pd(PPh_3)_4$	**5d**+**6d** (79%)	64/36
9	**2d**	MeOOC–CH=C(OMe)ONa	$Pd(PPh_3)_4$	**5c**+**6c** (84%)	66/34
10	**2d**	MeOOC–CH=C(Me)ONa	$Pd(PPh_3)_4$	**5d**+**6d** (82%)	66/34

[a] Yield for the mixture of products determined after flash chromatography.
[b] Regioselectivity determined by ^1H NMR of the crude reaction mixture.
[c] Reaction carried out under reflux of THF.

hypothesis is supported by the observation that the regioselectivity does not depend on the nature of the starting sulfonyl chloride (**2c** vs **2d**). With $PdCl_2(PhCN)_2$ as catalyst, the regioselectivity in favor of the linear products **5** ((*E*)-crotyl derivatives) suggests that a steric factor is controlling the C–C bond forming process. In the case of $Pd(PPh_3)_4$-catalyzed reactions it seems that the (crotyl)Pd(ligand) intermediate does not make any great difference for the Nu insertion into the non-substituted (less steric hindrance) and the methyl substituted center of the (allyl)palladium moiety. For more than 30 years it has been known that the regioselectivity of allylic alkylation,[86–95] allylic vinylation,[96–98] and allylic arylation[99–102] depends on the nature of the catalyst.

Although many more experiments should be carried out to approach a mechanistic interpretation of our results, we propose at this stage that (allyl)palladium intermediates **7** and **8** are formed by reactions of **2c** or **2d** with $PdCl_2(PhCN)_2$ and $Pd(PPh_3)_4$, respectively (Scheme 3). Intermediate **7** is expected to be more electrophilic than **8** and favors an anti mode of addition of the nucleophiles (Nu^-) onto the least sterically hindered allylic carbon center. In the case of **8**, the nucleophile undergoes first an oxidative addition or S_N2 displacement reaction at the palladium center. The resulting intermediate **9** undergoes then a reductive elimination reaction forming the C–C bond, a process, which is less demanding in terms of steric hindrance between secondary and tertiary allylic centers.



Scheme 3. Proposed mechanism for the desulfinylative allylation of Grignard reagents and sodium enolates.

Depending on the nature of the leaving group of the crotyl and 3-buten-2-yl electrophiles and ligand significant degree of retention of regiochemistry and stereochemistry has been observed for palladium-catalyzed allylic alkylation.[94,103–108]

We thus examined the desulfinylative allylation of *m*-tolylMgCl with 1-methylprop-2-enesulfonate (**3c**) and neopentyl (*E*)-2-butenesulfonate (**3d**). Using $Pd(PPh_3)_4$ as catalyst (5 mol %) in boiling THF, mixtures of **5b**+**6b** were obtained in 58 and 42% yields, respectively. Contrary to the reactions with sulfonyl chlorides **2c** and **2d** that led to the same 1:1 mixture of **5b**+**6b** (Table 5, entries 3, 6), we observed with the reactions of sulfonic esters **3c** and **3d** different proportions of products **5b** and **6b**, indicating partial retention of regioselectivity (Scheme 4).

It is known that iridium catalysts favor the more substituted allylic terminus in allylic alkylations.[109–117] This was also the case for the reaction of (*E*)-but-2-enesulfonyl chloride (**2d**) with the sodium salt of dimethyl malonate in the presence of $[Ir(COD)Cl]_2$ in THF at room temperature that produced a 1:4 mixture of products of allylation **5c** and **6c** (Scheme 5).

3. Conclusion

Allylic arylation and alkylation of Grignard reagents and sodium salts of dimethyl malonate and methyl acetoacetate can be carried out under smooth conditions in the presence of a palladium catalyst and using 2-alkenesulfonyl chlorides as electrophilic reagents. The latter undergo fast desulfinylations generating (allyl)palladium intermediates. The regioselectivity of the quenching of these intermediates by the nucleophilic reagents depends on the nature of the catalyst, but not on the nature of the starting alk-2-enesulfonyl chloride. For instance using either 1-methylprop-2-enesulfonyl chloride or (*E*)-but-2-enesulfonyl chloride the linear products are favored over the branched isomers (regioselectivity 95:5 or better) for arylMgCl and using 5 mol % of $PdCl_2(PhCN)_2$ in THF at room temperature. When branched isomers are targeted $[Ir(COD)Cl]_2$-catalyzed allylic allylation of (*E*)-but-2-ene-sulfonyl chlorides with the sodium salt of dimethyl malonate can be employed.

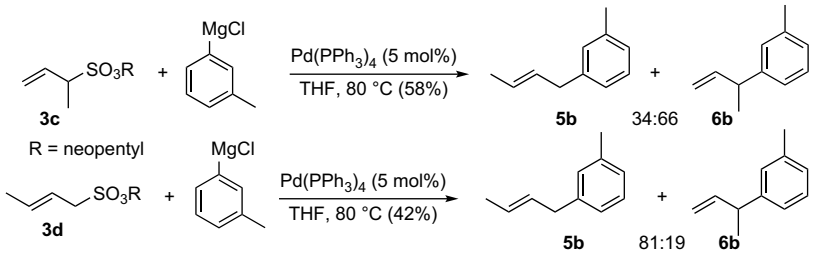
4. Experimental section

4.1. Methods

Unless stated otherwise, reactions were conducted in flame-dried glassware under a vacuum. THF was distilled before to use from sodium and benzophenone. Catalysts and ligands were purchased from Strem Chemical, Inc. All commercially available reagents are used without further purification. Solvents after reactions and extraction were evaporated in a rotatory evaporator under vacuum (solvents were removed cooling at −20 °C, in the case of low boiling point or low molecular mass compounds). TLC for reaction monitoring was performed on 60 F_{254} (Merck) with detection by UV light and charring with $KMnO_4$ or Pancaldi reagent. ^1H and ^{13}C NMR spectra were recorded by using Bruker-DPX-400 or Bruker-ARX-400 spectrometer at 400 MHz and 100.6 MHz, respectively, and are reported relative to Me_4Si (δ 0.0) or to the solvents residual ^1H-signal ($CH–Cl_3$, $\delta(H)$ 7.27). Data for ^1H NMR spectra are reported as follows: chemical shift (δ ppm), multiplicity, coupling constant (Hz), and integration. Data for ^{13}C NMR spectra reported in terms of chemical shift. IR spectra were recorded on a Perkin–Elmer-1420 spectrometer and are reported in frequency of absorption (cm^{-1}). High Resolution MALDI-TOF mass spectra were obtained from the Institute of Molecular and Biology Chemistry, Swiss Institute of Technology Mass Spectral Facility. Compounds **1c**,[118] **2a**,[62] **2b**,[119] **2d**[65] were prepared from known methods.

4.2. 1-Methylprop-2-ene-1-sulfonyl chloride (2c)

$(CF_3SO_2)_2NSiMe_3$ (0.78 mmol, 0.2 equiv) in anhyd CH_3CN (5 mL) was degassed by freeze-thaw cycles on the vacuum line. SO_2 (78 mmol, 20 equiv), dried through column packed with P_2O_5 and AlO_3, was transferred on the vacuum line to the MeCN solution frozen at −196 °C. The mixture was allowed to melt and to warm to −40 °C. After 30 min at this temperature but-2-enyl(trimethyl)silane (**1c**)



Scheme 4. Desulfinylative, regioselective allylic arylations with neopentyl sulfonates showing partial regioselectivity retention.

(3.9 mmol, 1 equiv) in MeCN (1 mL) was added slowly. The mixture was stirred at −40 °C for 6 h. After cooling to −78 °C, the excess of SO_2 and the solvent were evaporated under reduced pressure (10^{-3} Torr) to dryness (ca. 1 h). Halogenating agent (NCS 4.7 mmol, 1.2 equiv, dissolving in MeCN) was added to reaction mixture at −20 °C. After 2 h at this temperature, allylsulfonyl chloride formed. The residue was purified by flash chromatography (9:1 PE/EtOAc) to yield 68% as colorless oil. IR (film): 2920, 1360, 1235, 1160, 945, 735 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ=5.98 (m, 1H, H–C(3)), 5.62 (m, 2H, H–C(4)), 4.26 (m, 1H, H–C(2)), 1.72 (d, 3H, J=6.78 Hz, H–C(1)). ^{13}C NMR (100.6 MHz, $CDCl_3$): δ=132.5, 127.9, 77.5, 18.4. CIMS (NH_3): m/z=154 (27, [M]), 98 (100, [M−55]).

4.3. Neopentyl 2-methylprop-2-ene-1-sulfonate (3a)

To a solution of methallylsulfonyl chloride **2a** (8.36 g, 54 mmol, 1 equiv) in MeCN (14 mL) at 0 °C were added neopentyl alcohol (14.3 g, 0.16 mol, 3 equiv) and Et_3N (11.4 mL, 81.1 mmol, 1.5 equiv). The resulting mixture was warmed to 25 °C and stirred for 2 h. The reaction mixture was added to 50 mL of H_2O and extracted with EtOAc (70 mL, three times). The combined organic phases were dried (Na_2SO_4), evacuated in vacuo. The residue was purified by FC (8:2 PE/EtOAc): 10.4 g (93%), light yellow oil. IR (film): 2960, 1480, 1350, 1175, 965, 935, 840, 690 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ=5.14 (s, 1H, H–C(3)), 5.06 (s, 1H, H–C(3)), 3.83 (s, 2H, H–C(1)), 3.73 (s, 2H, H–C(1′)), 1.90 (s, 3H, Me–C(2)), 0.92 (s, 9H, H–C(3′)). ^{13}C NMR (100.6 MHz, $CDCl_3$): δ=133.6, 120.9, 79.6, 58.5, 32.2, 26.4, 22.7. CIMS (NH_3): m/z=224 (100, [M+18]), 154 (10, [M−52]), 71 (80, [M−135]). HRMS (MALDI-TOF): ($C_9H_{18}O_3SNa^+$), calcd: 229.0874; found: 229.0875.

4.4. Neopentyl 3-butene-2-sulfonate (3c)

Applying the same procedure as for the preparation of **3a**, starting from **2c**. The residue was purified by FC (9:1 PE/Et_2O) to give **3c**, 90%, as light yellow oil. IR (film): 2960, 1560, 1425, 1350, 1165, 960, 935, 830, 810, 655, 630 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ=5.92 (m, 1H, H–C(3)), 5.40 (m, 2H, H–C(4)), 3.86 (s, 2H, H–C(1′)), 3.82 (qn, 1H, J=7.83 Hz, H–C(2)), 1.53 (d, 3H, J=7.12 Hz, H–C(1)), 0.95 (s, 9H, H–C(3′)). ^{13}C NMR (100.6 MHz, $CDCl_3$): δ=131.2, 121.3, 79.2, 60.2, 42.6, 26.0, 14.5. CIMS (NH_3): m/z=224 (100, [M+18]), 154 (10, [M−52]), 71 (80, [M−135]). HRMS (MALDI-TOF): ($C_9H_{18}O_3SNa^+$), calcd: 229.0874; found: 229.0883.

4.5. Neopentyl (*E*)-but-2-ene-1-sulfonate (3d)

Applying the same procedure as for **3a**, starting from **2d**. FC (8:2 PE/EtOAc): 89% of **3d**, light yellow oil. IR (film): 2960, 1480, 1350, 1160, 960, 935, 840, 630 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ=5.81 (m, 1H, H–C(2)), 5.47 (m, 1H, H–C(3)), 3.79 (s, 2H, H–C(1′)), 3.70 (d, 2H, J=7.31 Hz, H–C(2)), 1.71 (d, 3H, J=6.41 Hz, H–C(4)), 0.91 (s, 9H, H–C(3′)). ^{13}C NMR (100.6 MHz, $CDCl_3$): δ=136.5, 117.5, 79.7, 54.3, 32.2, 26.5, 18.5. CIMS (NH_3): m/z=224 (100, [M+18]), 154 (10, [M−52]), 71 (80, [M−135]). HRMS (MALDI-TOF): ($C_9H_{18}O_3SNa^+$), calcd: 229.0874; found: 229.0874.

4.6. General procedure 1 for the desulfinylative allylation of Grignard reagents with sulfonyl chlorides

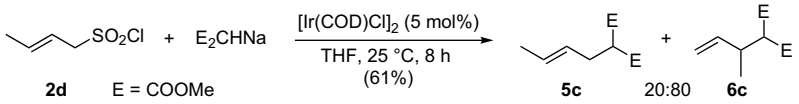
In a round bottom flask dried under *vacuum* was placed under N_2, the corresponding sulfonyl chloride (1 equiv), catalyst (5 mol %) in THF (4 mL) at 25 °C. Grignard reagent (1.5 equiv) was added dropwise to this solution over 5–10 min. The reaction mixture was stirred until complete disappearance of starting material. The reaction mixture was added to satd aq soln of NH_4Cl (15 mL) and extracted with ether (15 mL, three times). The combined organic layers were dried (Na_2SO_4), filtered, and concentrated under reduced pressure. The residue was purified by flash chromatography.

4.7. General procedure 2 for the desulfinylative allylation of sodium enolates with sulfonyl chlorides

NaH (1.5 equiv) and either dimethyl malonate or methyl acetoacetate (1.5 equiv) were mixed in THF (3 mL) and stirred at 0 °C for 20 min. This solution was then added dropwise to a round bottom flask containing sulfonyl chloride (1 equiv), catalyst (0.05 equiv) in THF (3 mL) at 25 °C. The reaction mixture was stirred until disappearance of starting material. The mixture was added to cold H_2O (15 mL) and extracted with ether (15 mL, three times). The combined organic layers were dried (Na_2SO_4), filtered, and concentrated under reduced pressure. The residue was purified by flash chromatography.

4.8. 1-Methyl-2-(2-methyl-2-propenyl)benzene (4a)[58]

Using the general procedure **1** for the reaction using 1.0 M soln of *o*-tolylmagnesium chloride (1.0 mL, 1.0 mmol, 1.5 equiv) with **2a** (0.1 g, 0.65 mmol, 1 equiv): 82 mg (87%), colorless oil. ^1H NMR



Scheme 5. Iridium-catalyzed regioselective allylation of dimethyl malonate salt with (*E*)-crotylsulfonyl chloride.

(400 MHz, $CDCl_3$): δ=7.16 (m, 4H, arom.), 4.84 (s, 1H, H–C(3)), 4.55 (s, 1H, H–C(3)), 3.34 (s, 2H, H–C(1)), 2.30 (s, 3H, Me–arom.), 1.77 (s, 3H, Me–C(2)). ^{13}C NMR (100.6 MHz, $CDCl_3$): δ=144.6, 130.5, 130.2, 127.7, 127.2, 111.9, 42.2, 23.1, 19.8. CIMS (NH_3): m/z=146 (40, [M]), 131 (100, [M−15]), 91 (33, [M−55]).

4.9. (2-Methylallyl)benzene (4b)[120]

Using the general procedure **1** for the reaction using 1.8 M soln of PhMgCl (0.56 mL, 1.0 mmol, 1.5 equiv) with **2a** (0.1 g, 0.65 mmol, 1 equiv): 70 mg (82%), colorless oil. Using the general procedure **1** for the reaction using 0.5 M soln of phenylzinc bromide (2.0 mL, 1.0 mmol, 1.5 equiv) instead of Grignard reagent with **2a** (0.1 g, 0.65 mmol, 1 equiv): 54 mg (57%), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ=7.40–7.05 (m, 5H, arom.), 4.84 (s, 1H, H–C(3)), 4.76 (s, 1H, H–C(3)), 3.31 (s, 2H, H–C(1)), 1.67 (s, 3H, Me–C(2)). ^{13}C NMR (100.6 MHz, $CDCl_3$): δ=139.8, 138.7, 128.9, 128.3, 126.1, 111.9, 44.7, 22.1. CIMS (NH_3): m/z=132 (91, [M]), 117 (100, [M−15]), 91 (49, [M−55]).

4.10. 1-Methyl-3-(2-methyl-2-propenyl)benzene (4c)[121]

Using the general procedure **1** for the reaction using 1.0 M soln of *m*-tolylmagnesium chloride (1.0 mL, 1.0 mmol, 1.5 equiv) with **2a** (0.1 g, 0.65 mmol, 1 equiv): 59 mg (62%), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ=7.05–6.88 (m, 4H, arom.), 4.88 (s, 1H, H–C(3)), 4.81 (s, 1H, H–C(3)), 3.35 (s, 2H, H–C(1)), 2.48 (s, 3H, Me–arom.), 1.75 (s, 3H, Me–C(2)). CIMS (NH_3): m/z=146 (56, [M]), 117 (100, [M−15]), 91 (41, [M−55]).

4.11. 3-(4-Methoxyphenyl)-2-methylprop-2-ene (4d)[122]

Using the general procedure **1** for the reaction using 0.5 M soln of *p*-methoxyphenylmagnesium bromide (2.0 mL, 1.0 mmol, 1.5 equiv) with **2a** (0.1 g, 0.65 mmol, 1 equiv): 83 mg (79%), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ=7.12 (d, J=8.6 Hz, 2H, arom.), 6.85 (d, J=8.6 Hz, 2H, arom.), 4.80 (s, 1H, H–C(1)), 4.73 (s, 1H, H–C(1)), 3.81 (s, 3H, OMe), 3.28 (s, 2H, H–C(3)), 1.69 (s, 3H, Me–C(2)). ^{13}C NMR (100.6 MHz, $CDCl_3$): δ=158.0, 145.5, 131.8, 129.8, 113.7, 111.6, 55.3, 43.8, 21.9. CIMS (NH_3): m/z=180 (2, [M+18]), 163 (9, [M+1]), 162 (75, [M]), 146 (32, [M−16]).

4.12. 1-(3-Methyl-3-butenyl)benzene (4e)[123]

Using the general procedure **1** for the reaction using 1.3 M soln of benzyl magnesium chloride (0.77 mL, 1.0 mmol, 1.5 equiv) with **2a** (0.1 g, 0.65 mmol, 1 equiv): 71 mg (75%), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ=7.30–7.12 (m, 5H, arom.), 4.78–4.73 (m, 2H, H–C(4)), 2.80 (m, 2H, H–C(1)), 2.35 (m, 2H, H–C(2)), 1.80 (s, 3H, Me–C(3)). ^{13}C NMR (100.6 MHz, $CDCl_3$): δ=145.3, 142.1, 128.2, 128.1, 125.1, 110.0, 39.5, 34.1, 22.5. CIMS (NH_3): m/z=146 (9, [M]), 108 (14, [M−38]), 91 (100, [M−55]).

4.13. 1-(4-Methylpent-4-enyl)benzene (4f)[124]

Using the general procedure **1** for the reaction using 1.0 M soln of 2-phenylethylmagnesium chloride (1.0 mL+0.7 mL, 1.65 mmol, 2.5 equiv) with **2a** (0.1 g, 0.65 mmol, 1 equiv): 65 mg (62%), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ=7.23–7.11 (m, 5H, arom.), 4.75 (s, 1H, H–C(5)), 4.62 (s, 1H, H–C(5)), 2.53 (t, J=7.85 Hz, 2H, H–C(1)), 1.98 (t, J=7.41 Hz, 2H, H–C(3)), 1. 69 (m, 2H, H–C(2)), 1.65 (s, 3H, Me–C(4)). ^{13}C NMR (100.6 MHz, $CDCl_3$): δ=146.0, 142.8, 128.7, 128.6, 126.0, 110.3, 37.6, 35.7, 29.6, 22.7. CIMS (NH_3): m/z=160 (9, [M]), 144 (4, [M−26]), 104 (100, [M−56]).

4.14. 1-Allyl-2-methylbenzene (4h)[125]

Using the general procedure **1** for the reaction using 1.0 M soln of *o*-tolylmagnesium chloride (1.1 mL, 1.1 mmol, 1.5 equiv) with sulfonyl chloride **2b** (0.1 g, 0.72 mmol, 1 equiv): 72 mg (76%), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ=7.35–7.10 (m, 4H, arom.), 6.01 (m, 1H, H–C(2)), 5.12 (m, 2H, H–C(3)), 3.44 (d, J=6.39 Hz, 2H, H–C(1)), 2.34 (s, 3H, Me–arom.). CIMS (NH_3): m/z=132 (40, [M]), 91 (100, [M−41]).

4.15. 4-Allylanisole (4i)[126]

Using the general procedure **1** for the reaction using 0.5 M soln of *p*-methoxyphenylmagnesium bromide (2.2 mL, 1.1 mmol, 1.5 equiv) with **2b** (0.1 g, 0.72 mmol, 1 equiv): 90 mg (85%), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ=7.06 (d, J=8.56 Hz, 2H, arom.), 6.80 (d, J=8.56 Hz, 2H, arom.), 5.91 (m, 1H, H–C(2)), 4.97 (m, 2H, H–C(3)), 3.71 (s, 3H, OMe), 3.26 (d, J=6.59 Hz, 2H, H–C(1)). CIMS (NH_3): m/z=148 (21, [M]), 147 (100, [M−1]), 132 (19, [M−16]), 91 (44, [M−57]).

4.16. Dimethyl 2-(2-methyl-2-propenyl)malonate (4k)[127]

Using the general procedure **2** for the reaction using NaH (40 mg, 0.97 mmol, 1.5 equiv), dimethyl malonate (0.130 g, 0.97 mmol, 1.5 equiv) with **2a** (0.1 g, 0.65 mmol, 1 equiv): 92 mg (76%), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ=4.76 (s, 1H, H–C(3)), 4.69 (s, 1H, H–C(3)), 3.74 (s, 6H, OMe), 3.59 (t, J=7.7 Hz, 1H, H–CX_2), 2.59 (d, J=7.7 Hz, 2H, H–C(1)), 1.72 (s, 3H, Me–C(2)). ^{13}C NMR (100.6 MHz, $CDCl_3$): δ=170.6, 139.8, 116.6, 49.2, 48.6, 38.1, 23.2. CIMS (NH_3): m/z=204 (19, [M+18]), 171 (100, [M−15]), 155 (11, [M−31]).

4.17. Methyl 2-acetyl-4-methyl-4-pentenoate (4l)[128]

Using the general procedure **2** for the reaction using NaH (40 mg, 0.97 mmol, 1.5 equiv), methyl acetoacetate (0.11 g, 0.97 mmol, 1.5 equiv) with **2a** (0.1 g, 0.65 mmol, 1 equiv): 86 mg (78%), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ=4.70 (s, 1H, H–C(5)), 4.61 (s, 1H, H–C(5)), 3.64 (m, 4H, OMe+H–C(2)), 2.48 (m, 2H, H–C(3)), 2.18 (s, 3H, Me–C(O)), 1.67 (s, 3H, Me–C(4)). ^{13}C NMR (100.6 MHz, $CDCl_3$): δ=202.7, 170.2, 142.1, 112.6, 58.3, 52.7, 36.1, 26.3, 22.6. CIMS (NH_3): m/z=188 (85, [M+18]), 171 (100, [M+1]), 139 (14, [M−31]).

4.18. Dimethyl 2-allylmalonate (4m)[129]

Using the general procedure **2** for the reaction using NaH (43 mg, 1.07 mmol, 1.5 equiv), dimethyl malonate (0.13 g, 1.07 mmol, 1.5 equiv) with **2b** (0.1 g, 0.72 mmol, 1 equiv): 114 mg (92%), colorless oil. The spectral data (^{1}H NMR and ^{13}C NMR) of the product are identical with those described in the literature for this compound.[131] ^{1}H NMR (400 MHz, $CDCl_3$): δ=5.71 (m, 1H, H–C(2)), 5.12 (m, 2H, H–C(3)), 3.74 (s, 6H, OMe), 3.48 (t, J=7.2 Hz, 1H, H–CX_2), 2.67 (t, J=7.4 Hz, 2H, H–C(1)). CIMS (NH_3): m/z=173 (9, [M+1]), 172 (100, [M]), 140 (6, [M−32]).

4.19. Methyl 2-acetylpent-4-enoate (4n)[130]

Using the general procedure **2** for the reaction using NaH (43 mg, 1.07 mmol, 1.5 equiv), methyl acetoacetate (0.13 g, 1.07 mmol, 1.5 equiv) with **2b** (0.1 g, 0.72 mmol, 1 equiv): 100 mg (89%), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ=5.76 (m, 1H, H–C(4)), 5.10 (m, 2H, H–C(5)), 3.74 (s, 3H, OMe), 3.54 (t, J=7.1 Hz, 1H, H–C(2)), 2.59 (m, 2H, H–C(3)), 2.21 (s, 3H, Me–C(O)). CIMS (NH_3): m/z=174 (5, [M+18]), 156 (100, [M]), 142 (9, [M−14]).

4.20. (*E*)-1-(But-2-enyl)-2-methylbenzene (5a)[131] and 1-(but-3-en-2-yl)-2-methylbenzene (6a)[101]

Using the general procedure **1** for the reaction using 1.0 M soln of *o*-tolylmagnesium chloride (1.0 mL, 1.0 mmol, 1.5 equiv) with **2c** (0.1 g, 0.65 mmol, 1 equiv): 65 mg (69%), colorless oil. Using the general procedure **1** for the reaction using 1.0 M soln of *o*-tolylmagnesium chloride (1.0 mL, 1.0 mmol, 1.5 equiv) with **2d** (0.1 g, 0.65 mmol, 1 equiv): 71 mg (75%), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) of **5a**: δ=7.21 (s, 4H, arom.), 5.62 (m, 1H, H–C(2)), 5.48 (m, 1H, H–C(3)), 3.33 (d, 2H, 6.61 Hz, H–C(1)), 2.33 (s, 3H, Me–arom.), 1.71 (d, 3H, 6.38 Hz, H–C(4)). ^{1}H NMR (400 MHz, $CDCl_3$) of **6a**: δ=7.21 (s, 4H, arom.), 6.02 (m, 1H, H–C(3)), 5.10 (m, 2H, H–C(4)), 3.73 (qn, 1H, 6.98 Hz, H–C(2)), 2.33 (s, 3H, Me–arom.), 1.38 (d, 3H, 6.98 Hz, H–C(1)). CIMS (NH_3): *m*/*z*=147 (8, [M+1]), 146 (54, [M]), 105 (100, [M−41]), 91 (36, [M−55]).

4.21. (*E*)-1-(But-2-enyl)-3-methylbenzene (5b)[132] and 1-(but-3-en-2-yl)-3-methylbenzene (6b)[133]

Using the general procedure **1** for the reaction using 1.0 M soln of *m*-tolylmagnesium chloride (1.0 mL, 1.0 mmol, 1.5 equiv) with **2c** (0.1 g, 0.65 mmol, 1 equiv): 53 mg (56%), colorless oil. Using the general procedure **1** for the reaction using 1.0 M soln of *m*-tolylmagnesium chloride (1.0 mL, 1.0 mmol, 1.5 equiv) with **2d** (0.1 g, 0.65 mmol, 1 equiv): 64 mg (68%), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) of **5b**: δ=7.22–7.17 (m, 2H, arom.), 7.07–7.01 (m, 2H, arom.), 5.66 (m, 2H, H–C(2) and H–C(3)), 3.30 (d, 2H, *J*=6.06 Hz, H–C(1)), 2.35 (s, 3H, Me–arom.), 1.70 (d, 3H, 5.76 Hz, H–C(4)). ^{1}H NMR (400 MHz, $CDCl_3$) of **6b**: δ=7.22–7.17 (m, 2H, arom.), 7.07–7.01 (m, 2H, arom.), 6.03 (m, 1H, H–C(3)), 5.07 (m, 2H, H–C(4)), 3.45 (qn, 1H, *J*=6.72 Hz, H–C(2)), 2.34 (s, 3H, Me-arom.), 1.37 (d, 3H, *J*=6.96 Hz, H–C(1)). CIMS (NH_3): *m*/*z*=147 (11, [M+1]), 146 (92, [M]), 131 (100, [M−15]), 105 (19, [M−41]), 91 (28, [M−55]).

4.22. (*E*)-Dimethyl 2-(but-2-enyl)malonate (5c)[129] and dimethyl 2-(but-3-en-2-yl)malonate (6c)[129]

Using the general procedure **2** for the reaction using NaH (40 mg, 0.97 mmol, 1.5 equiv), dimethyl malonate (0.11 g, 0.97 mmol, 1.5 equiv) with **2c** (0.1 g, 0.65 mmol, 1 equiv): 92 mg (76%), colorless oil. Using the general procedure **2** for the reaction using NaH (40 mg, 0.97 mmol, 1.5 equiv), dimethyl malonate (0.11 g, 0.97 mmol, 1.5 equiv) with **2d** (0.1 g, 0.65 mmol, 1 equiv): 101 mg (84%), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) of **5c**: δ=5.53 (m, 1H, H–C(2)), 5.36 (m, 1H, H–C(3)), 3.72 (s, 6H, OMe), 3.39 (t, *J*=7.25 Hz, 1H, C*H*X$_2$), 2.56 (m, 2H, H–C(1)), 1.62 (d, *J*=6.45 Hz, 3H, H–C(4)). ^{1}H NMR (400 MHz, $CDCl_3$) of **6c**: δ=5.75 (m, 1H, H–C(3)), 5.04 (m, 2H, H–C(4)), 3.72 (s, 3H, OMe), 3.69 (s, 3H, OMe), 3.30 (d, *J*=8.53 Hz, 1H, C*H*X$_2$), 2.94 (m, 1H, H–C(2)), 1.09 (d, *J*=6.72 Hz, 3H, H–C(1)). CIMS (NH_3): *m*/*z*=204 (12, $[M+18]^+$), 186 (100, $[M]^+$), 171 (15, $[M-15]^+$), 126 (57, $[M-60]^+$).

4.23. (*E*)-Methyl 2-acetylhex-4-enoate (5d)[134] and methyl 2-acetyl-3-methylpent-4-enoate (6d)[134]

Using the general procedure **2** for the reaction using NaH (40 mg, 0.97 mmol, 1.5 equiv), methyl acetoacetate (0.13 g, 0.97 mmol, 1.5 equiv) with **2c** (0.1 g, 0.65 mmol, 1 equiv): 87 mg (79%), colorless oil. Using the general procedure **2** for the reaction using NaH (40 mg, 0.97 mmol, 1.5 equiv), methyl acetoacetate (0.13 g, 0.97 mmol, 1.5 equiv) with **2d** (0.1 g, 0.65 mmol, 1 equiv): 90 mg (82%), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) of **5d**: δ=5.51 (m, 1H, H–C(4)), 5.33 (m, 1H, H–C(5)), 3.71 (s, 3H, OMe), 3.48 (t, *J*=7.31 Hz, 1H, H–C(2)), 2.51 (m, 2H, H–C(3)), 2.21 (s, 3H, Me), 1.61 (d, *J*=6.43 Hz, 3H, H–C(6)). ^{1}H NMR (400 MHz, $CDCl_3$) of **6d**: δ=5.69 (m, 1H, H–C(4)), 5.03 (m, 2H, H–C(5)), 3.71 (s, 3H, OMe), 3.37 (d, *J*=9.50 Hz, 1H, H–C(2)), 2.96 (m, 1H, H–C(3)), 2.18 (s, 3H, Me), 1.09 (d, *J*=6.66 Hz, 3H, Me–C(3)). CIMS (NH_3): *m*/*z*=171 (10, $[M+1]^+$), 170 (100, $[M]^+$), 151 (5, $[M-19]^+$), 126 (12, $[M-44]^+$).

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