Radical β-addition to acyclic α-(arylsulfinyl) enones: Pummerer-type rearrangement

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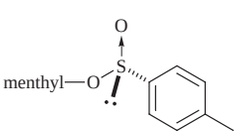
The reaction of (*S*,*E*)-3-(*p*-tolylsulfinyl)pent-3-en-2-one with an isopropyl radical, generated from isopropyl iodide and triethylborane, gives the non-stereoselective addition product and an unexpected α-(arylsulfanyl) enone which is formed through a radical addition and subsequent Pummerer-type rearrangement. The formation of the α-(arylsulfanyl) enone depends upon the additives used as well as the aryl group on the sulfur.

Introduction

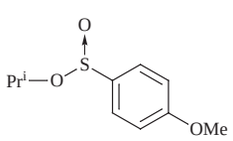
Recently, radical reactions have been recognized as a means for stereoselective carbon–carbon bond formation.[1] There are a number of reports of asymmetric radical reactions using chiral auxiliaries.[2] While the sulfinyl group has been recognized as an attractive chiral auxiliary in radical 1,2-asymmetric induction,[3] there are only a few reports on radical β-addition to chiral vinyl sulfoxides.[4] We have reported a stereoselective intermolecular radical β-addition reaction of 2-(arylsulfinyl)cycloalk-2-enones,[5] in which a chiral sulfinyl group having a sterically bulky aryl group such as a 2,4,6-triisopropylphenyl or 2,4,6-trimethylphenyl group shows extremely high diastereoselectivity in the radical β-addition. We report herein the results of an intermolecular β-addition of alkyl radicals to acyclic α-(arylsulfinyl) enones.

Results and discussion

We studied the radical β-addition to acyclic α-(arylsulfinyl) enones **7a**–**d** which were prepared from the sulfinates **1**–**4** in



(*S*)-**1**



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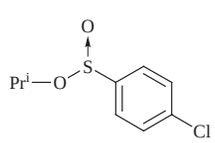

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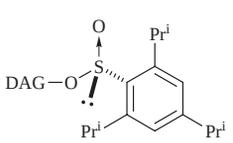
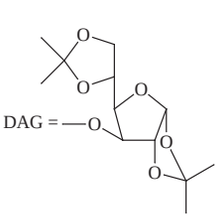
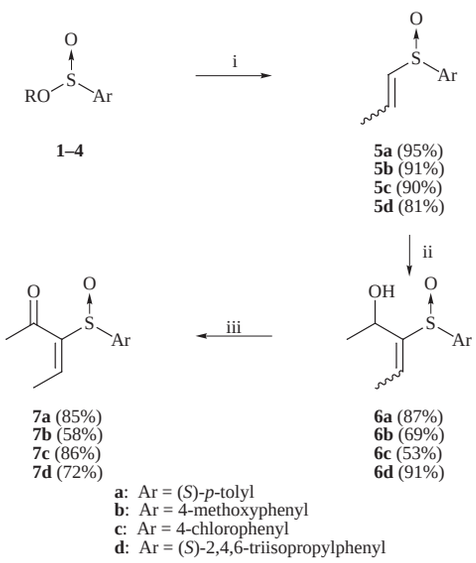


(*S*)-**4**



three steps. The reaction of sulfinates **1**–**4** with prop-1-enylmagnesium bromide, which was prepared from magnesium and a mixture of (*E*)- and (*Z*)-1-bromoprop-1-ene, gave a mixture of (*E*)- and (*Z*)-aryl prop-1-enyl sulfoxides **5** in good yields (Scheme 1).[6] A mixture of (*E*)- and (*Z*)-**5** was treated with 2 equiv. of LDA at −100 °C and subsequently with an excess of acetaldehyde to afford the 3-(arylsulfinyl)pent-3-en-2-ol **6**



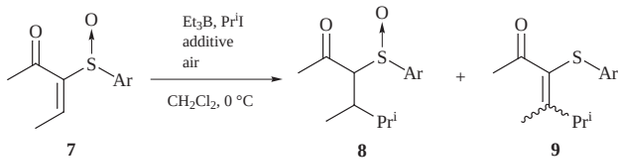
Scheme 1 *Reagents and conditions*: i, $CH_3CH{=}CHMgBr$, THF, 0 °C ⟶ rt; ii, LDA, CH_3CHO, THF, −100 °C; iii, Jones oxidation or Swern oxidation, and subsequent purification by recrystallization (**7a** and **7d**) or flash column chromatography (**7c**)

which was composed mainly of the (*E*)-isomer due to *cis*–*trans* isomerization during the reaction.[7] Oxidation of **6** was accomplished by Jones oxidation[8] or Swern oxidation[7a] to give the 3-(arylsulfinyl)pent-3-en-2-one **7**. (*E*)-**7a** and (*E*)-**7d** could be isolated by recrystallization from diethyl ether and (*E*)-**7c** by flash column chromatography. A mixture of (*E*)- and (*Z*)-**7b** in an *E*:*Z* ratio of 72:28 was used without separation of the isomers in the following radical reaction.

The β-addition of an isopropyl radical to α-(arlysulfinyl) enones **7a**–**7d** was carried out as follows. To a degassed solution of the α-(arylsulfinyl) enone **7** in CH_2Cl_2 (0.01 mol dm^{-3}) was added isopropyl iodide (10 equiv.) and triethylborane (10 equiv.) as a radical initiator[9] at 0 °C, and air was continuously passed through the solution *via* a needle by a microfeeder.[10] The results are shown in Table 1.

The reaction of (*S*,*E*)-3-(*p*-tolylsulfinyl)pent-3-en-2-one **7a** with an isopropyl radical gave a diastereomeric mixture of the addition products **8a** with low diastereoselectivity (entry 1). The addition product with an ethyl radical generated from triethylborane was not formed.[11] Reactions in the presence of $TiCl_2(OP^i)_2$,[12] $Ti(OPr^i)_4$, $ZnBr_2$, $BF_3{\cdot}OEt_2$ or K_2CO_3 did not alter the stereoselectivity substantially (entries 2–6). We expected a low stereoselectivity, as the *p*-tolyl group is not as effective as the 2,4,6-triisopropylphenyl or 2,4,6-trimethylphenyl group in inducing high stereoselectivity as we observed

Table 1 Radical β-addition to α-(arylsulfinyl) enones **7** with isopropyl iodide and triethylborane



7 **8** **9**

a: Ar = (*S*)-*p*-tolyl
b: Ar = 4-methoxyphenyl
c: Ar = 4-chlorophenyl
d: Ar = (*S*)-2,4,6-triisopropylphenyl

				8		**9**
Entry	Enone	Additive	*t*/h	Yield (%)	Ratio	Yield (%)
1	**7a**	none	1	75	21:13:41:19	12
2	**7a**	$TiCl_2(OPr^i)_2$	1	60	13:20:35:32	23
3	**7a**	$Ti(OP^i)_4$	1	80	26:14:48:12	10
4	**7a**	$ZnBr_2$	1	79	39:11:40:10	16
5	**7a**	$BF_3{\cdot}OEt_2$	1	79	45:10:35:10	17
6	**7a**	K_2CO_3	1	80	30:15:42:13	6
7	**7a**	*p*-TsOH	1	0	—	57
8	**7b**[a]	none	2	77	17:11:56:16	21
9	**7c**	none	1	91	21:13:49:17	6
10	**7d**	none	1.5	0	—	58
11	**7d**	$TiCl_2(OP^i)_2$	45	0	—	23
12	**7d**	$SiMe_3Cl$	1.5	0	—	33
13	**7d**	*p*-TsOH	0.7	0	—	99
14	**7d**	galvinoxyl	3 days	no reaction		

[a] An $E:Z = 72:28$ mixture was used.

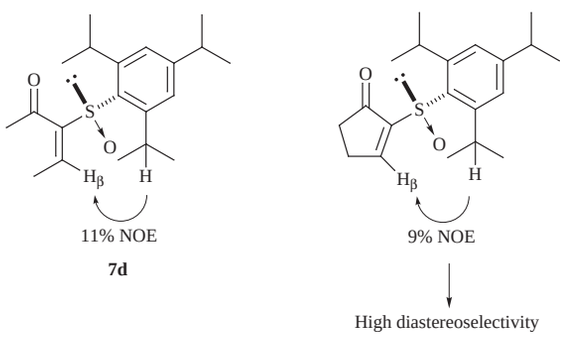
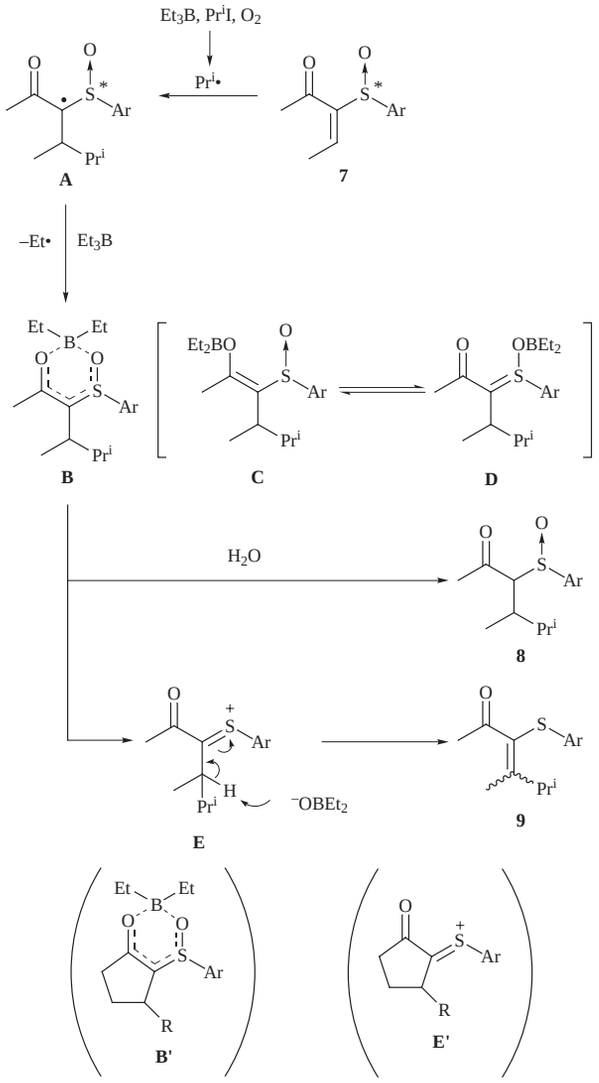


Fig. 1

in the reaction of 2-(arylsulfinyl)cyclopent-2-enones.[5] It was, however, surprising that an unexpected product, 4,5-dimethyl-3-(*p*-tolylsulfanyl)hex-3-en-2-one **9a**, was formed besides the addition products **8a**. The yield of the α-(arylsulfanyl) enone **9a** increased when the reaction was carried out in the presence of *p*-TsOH, where the addition product was not obtained at all (entry 7). The yield of the α-(arylsulfanyl) enone **9** increased in the reaction of (*E*)-3-(4-methoxyphenylsulfinyl)pent-3-en-2-one **7b** (entry 8) and decreased in the case of 3-(4-chlorophenylsulfinyl)pent-3-en-2-one **7c** (entry 9). Next, we examined the radical β-addition to (*S*,*E*)-3-(2,4,6-triisopropylphenylsulfinyl)pent-3-en-2-one **7d** which has a significant nuclear Overhauser effect (11%) between the methine proton of the *o*-isopropyl group and the β-vinyl proton in the ^{1}H NMR spectrum. Since 2-(2,4,6-triisopropylphenylsulfinyl)cyclopent-2-enone, which also has a significant nuclear Overhauser effect between these protons, shows extremely high stereoselection in the radical β-addition,[5] high stereoselectivity was anticipated in the radical β-addition to α-(arylsulfinyl) enone **7d** (see Fig. 1).

However, formation of the α-(arylsulfanyl) enone **9d** was observed in the reaction of α-(arylsulfinyl) enone **7d**, with no addition product **8d** being formed (entries 10–12). The α-(arylsulfanyl) enone **9d** was even obtained almost quantitatively when *p*-TsOH was added to the reaction mixture (entry 13). Both reactions to form the addition product **8d** and the α-(arylsulfanyl) enone **9d** seemed to proceed *via* a radical pathway at least in the first step of the alkyl radical addition, because both reactions were completely suppressed by a radical scavenger (entry 14). The presumed reaction mechanism is shown in Scheme 2.

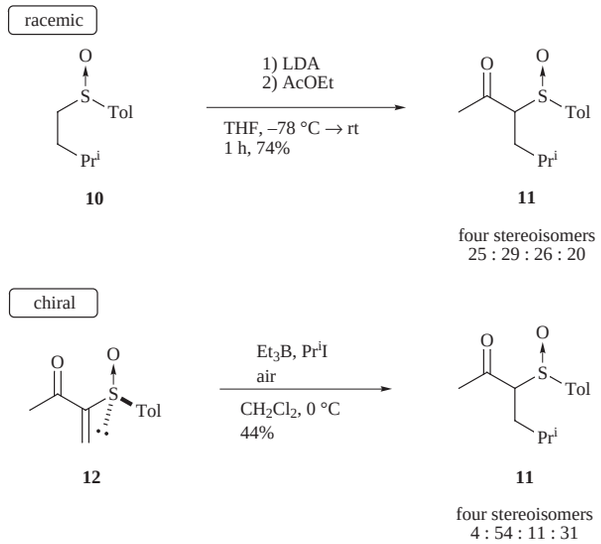
It is well recognized that enones react with alkyl radicals generated from trialkylborane to form a boron enolate *via* a carbon radical α to the carbonyl group.[9,13] Thus, an isopropyl radical generated from isopropyl iodide by the action of triethylborane with oxygen, attacks the olefinic carbon β to the carbonyl to form a carbon radical α to the carbonyl (**A**), which then reacts with triethylborane to form the cyclic intermediate **B** or the rapidly equilibrated boron enolates **C** and **D**. Hydrolysis of the intermediate gives the addition product **8**. However, the Pummerer-type products **9** are formed in the present reaction of α-(arylsulfinyl) enones probably because of the easy formation of the thionium intermediate **E** from the intermediate **B**. On the other hand, the radical reaction of the 2-(arylsulfinyl)cycloalk-2-enones produced no such Pummerer-type products and induced no racemization of the substrate (see below), due to the difficult formation of the corresponding intermediate **B**′ and the subsequent intermediate **E**′, shown in Scheme 2.[5] The S–O bond fission in **B** forms **E** and the subsequent proton abstraction from the β-carbon gives the α-(arylsulfanyl) enone **9** as a mixture of (*E*)- and (*Z*)-isomers. Since the S–O bond fission is the rate-determining step in the Pummerer reaction of sulfoxides having an electron-withdrawing group at the α-position,[14] the electronic nature of the substituent on the sulfur should have an influence on this step. In the reaction of the α-(arylsulfinyl) enone **7b** having an electron-donating 4-methoxyphenyl group, the formation of α-(arylsulfanyl) enone **9b** increases due to its thionium-stabilizing effect (Table 1, entry 8), whereas the reaction of the α-(arylsulfanyl) enone **7c** having an electron-withdrawing 4-chlorophenyl group decreases the stability of intermediate **E** and hence the yield of α-(arylsulfanyl) enone **9c** (Table 1, entry 9). *p*-TsOH would accelerate the S–O bond fission to form the thionium ion intermediate **E**, thus leading to the α-(arylsulfanyl) enone **9** exclusively (Table 1, entries 7 and 13). This assumption is quite reasonable, since acids are known to



Scheme 2

catalyze Pummerer-type reactions from sulfoxides to α-(arylsulfanyl) enones.[15] If this mechanistic pathway is correct then the sulfoxide should racemize during the formation of the cyclic boron enolate **B**. To verify this the following experiment was carried out.

(*S*)-3-(*p*-Tolylsulfinyl)but-3-en-2-one **12**, prepared according to the literature,[8,16] was treated with isopropyl iodide and triethylborane as described above to give the addition product **11** in 44% yield and the ethyl adduct (38% yield) (Scheme 3). HPLC analysis (CHIRALCEL OB-H) of the addition product **11** showed four stereoisomers in a ratio of 4 : 54 : 11 : 31 in order of elution. The retention times for these four stereoisomers were in accord with those for the products obtained on treatment of the racemic isopentyl *p*-tolyl sulfoxide **10** with lithium diisopropylamide and subsequently with ethyl acetate. These results show that the radical addition gives the racemized sulfoxide **11**, supporting the formation of the cyclic boron enolate intermediate **B**.



Scheme 3

Experimental

General

Diethyl ether (ether) and THF were distilled before use from a deep blue solution resulting from addition of benzophenone and sodium. CH_2Cl_2 was distilled from calcium hydride. All reactions were monitored by thin layer chromatography on 0.25 mm Merck silica gel (60F-254) precoated glass plates. TLC plates were visualized with UV light and 7% phosphomolybdic acid or *p*-anisaldehyde in ethanol. Column chromatography was carried out on a column packed with Fuji Silysia silica gel BW-200. Melting points were measured on a Yanaco micro-melting point apparatus and are uncorrected. ^{1}H NMR (200 MHz) and ^{13}C NMR (50.3 MHz) spectra for solutions in $CDCl_3$ were recorded on a Varian Gemini-200 instrument, chemical shifts (δ) are expressed in ppm downfield from internal tetramethylsilane, and *J* values are given in Hz. Infrared spectra were recorded on a JASCO FTIR-200 spectrometer. Mass spectra (eV) were recorded on a Hitachi M-2000 spectrometer. Microanalyses were performed with a Perkin-Elmer-240 instrument. Optical rotations were measured on a JASCO DIP-4 polarimeter operating at $\lambda = 589$ nm corresponding to the sodium D line, in the indicated solvent with concentration in grams of solute per 100 cm^3. HPLC analyses were performed on a JASCO TRI ROTOR IV using 4.6 × 150 mm COSMOSIL and 4.6 × 250 mm CHIRALCEL OB-H packed columns (flow rate, 0.5 cm^3 min^{-1}).

Preparation of the acyclic α-sulfinyl enones

4-Methoxyphenyl prop-1-enyl sulfoxide 5b. To a solution of isopropyl 4-methoxybenzenesulfinate[17] **2** (2.28 g, 10.7 mmol) in THF (11 cm^3) was added dropwise a solution of prop-1-enylmagnesium bromide, prepared from 1-bromoprop-1-ene (1.46 cm^3, 17.1 mmol) and magnesium (389 mg, 16 mmol) in THF (26 cm^3), at 0 °C over a period of 5 min. After stirring for 10 min at room temperature, the mixture was quenched with saturated aqueous NH_4Cl (10 cm^3) at 0 °C and concentrated under reduced pressure. The aqueous mixture was extracted with Et_2O (3 × 5 cm^3). The combined organic extracts were washed with saturated aqueous $NaHCO_3$ (5 cm^3), brine (5 cm^3), dried over Na_2SO_4, and concentrated to give the crude sulfoxide, which was purified by column chromatography (hexane–ethyl acetate, 40 : 60) to give the sulfoxide **5b** (1.91 g, 91%) in an *E* : *Z* ratio of 73 : 27. (*E*)-**5b** (Found: C, 61.18; H, 6.31. $C_{10}H_{12}O_2S$ requires C, 61.20; H, 6.16%); TLC R_f 0.37 (hexane–ethyl acetate, 40 : 60); ν_{max}(neat)/cm^{-1} 2950, 1595, 1500, 1440, 1305, 1260 and 1030; δ_H 1.91 (3 H, dd, *J* 1.6, 6.8, C*H*$_3$CH=), 3.85 (3 H, s, OCH$_3$), 6.23 (1 H, dq, *J* 1.6, 15.1, CH$_3$CH=C*H*), 6.58 (1 H, dq, *J* 6.8, 15.1, CH$_3$C*H*=CH), 6.94–7.08 (2 H, m, ArH) and 7.50–7.62 (2 H, m, ArH); δ_C 17.4, 55.3, 114.6, 126.3, 135.0, 135.3, 136.1 and 161.6; *m*/*z* (EI) 196 (M$^+$, 10%), 155 (50) and 148 (100). (*Z*)-**5b**: TLC R_f = 0.27 (hexane–ethyl acetate, 40 : 60); ν_{max}(neat)/cm^{-1} 2945, 1590, 1500, 1460, 1305, 1250 and 1035; δ_H 2.13 (3 H, d, *J* 5.5, C*H*$_3$CH=), 3.85 (3 H, s, OCH$_3$), 6.12–6.33 (2 H, m, CH=CH), 6.94–7.08 (2 H, m, ArH) and 7.50–7.62 (2 H, m, ArH); δ_C 15.0, 55.4, 114.8, 125.8, 135.5, 136.2, 138.0 and 161.7.

4-Chlorophenyl prop-1-enyl sulfoxide 5c. The reaction was carried out as described above using isopropyl 4-chlorobenzenesulfinate[17] **3** (2.46 g, 11.3 mmol) to give the sulfoxide **5c** (2.04 g, 90%) in an *E*:*Z* ratio of 71:29. (*E*)-**5c** (Found: C, 53.66; H, 4.59. C_9H_9ClOS requires C, 53.87; H, 4.52%); TLC R_f = 0.54 (hexane–ethyl acetate, 40:60); ν_{max}(neat)/cm^{-1} 3015, 2910, 1630, 1580, 1480, 1445, 1390, 1090 and 1040; δ_H 1.92 (3 H, dd, *J* 1.5, 6.7, CH_3), 6.24 (1 H, dq, *J* 1.5, 15.2, CH_3CH=C*H*), 6.64 (1 H, dq, *J* 6.7, 15.2, CH_3CH=CH) and 7.40–7.62 (4 H, m, ArH); δ_C 17.7, 125.7, 129.4, 136.0, 136.9, 137.2 and 142.7; *m*/*z* (EI) 200 (M^+, 21%), 152 (100) and 117 (54). (*Z*)-**5c**: TLC R_f = 0.44 (hexane–ethyl acetate, 40:60); ν_{max}(neat)/cm^{-1} 3015, 2950, 1630, 1480, 1390, 1090 and 1040; δ_H 2.16 (3 H, dd, *J* 1.2, 6.7, CH_3), 6.15–6.42 (2 H, m, CH=CH) and 7.40–7.62 (4 H, m, ArH); δ_C 15.0, 125.2, 129.2, 136.5, 137.1, 137.5 and 142.9.

(*R*)-Prop-1-enyl 2,4,6-triisopropylphenyl sulfoxide 5d. The reaction was carried out as described above using (*S*)-diacetone D-glucosyl 2,4,6-triisopropylbenzenesulfinate[5] (*S*)-**4** (4.94 g, 9.67 mmol) to give the sulfoxide **5d** (2.29 g, 81%). (*E*)-**5d** (Found: C, 73.68; H, 9.51. $C_{18}H_{28}OS$ requires C, 73.92; H, 9.65%); TLC R_f = 0.26 (hexane–ethyl acetate, 80:20); $[\alpha]_D^{24}$ −63.1 (*c* 0.482 in $CHCl_3$); ν_{max}(neat)/cm^{-1} 2960, 1600, 1470, 1050 and 1030; δ_H 1.23, 1.25 and 1.32 [18 H, 3 × d, *J* 6.7, 6.8, 6.8, 3 × CH(CH_3)$_2$], 2.10 (3 H, dd, *J* 1.6, 7.1, CH_3CH=CH), 2.75–3.01 [1 H, m, C*H*(CH_3)$_2$], 3.85–4.08 [2 H, m, 2 × C*H*(CH_3)$_2$], 6.27 (1 H, dq, *J* 7.1, 9.9, CH_3CH=CH), 6.75 (1 H, dq, *J* 1.6, 9.9, CH_3CH=C*H*) and 7.08 (2 H, s, ArH); δ_C 14.7, 24.0, 24.8, 28.8, 34.3, 123.1, 135.3, 135.9, 136.9, 149.8 and 152.4; *m*/*z* (EI) 292 (M^+, 19%), 275 (100), 233 (39), 191 (74) and 149 (66). (*Z*)-**5d** (Found: C, 73.62; H, 9.64. $C_{18}H_{28}OS$ requires C, 73.92; H, 9.65%); TLC R_f = 0.37 (hexane–ethyl acetate, 80:20); $[\alpha]_D^{23}$ +203 (*c* 0.350 in $CHCl_3$); ν_{max}(neat)/cm^{-1} 2960, 1600, 1470 and 1055; δ_H 1.18–1.39 [18 H, m, 3 × CH(CH_3)$_2$], 1.92 (3 H, d, *J* 5.0, CH_3CH=CH), 2.75–3.01 [1 H, m, C*H*(CH_3)$_2$], 3.79–4.05 [2 H, m, 2 × C*H*(CH_3)$_2$], 6.36–6.51 (2 H, m, CH=CH) and 7.06 (2 H, s, ArH); δ_C 17.8, 23.7, 24.8, 28.2, 34.3, 123.0, 133.5, 134.0, 134.7, 150.3 and 152.6; *m*/*z* (EI) 292 (M^+, 16%), 275 (100), 233 (40), 191 (77) and 149 (69).

(S_S)-3-(*p*-Tolylsulfinyl)pent-3-en-2-ol 6a. To a solution of LDA (13.0 mmol) was added a solution of (*R*)-prop-1-enyl *p*-tolyl sulfoxide **5a**[6] (1.06 g, 5.89 mmol) in THF (6 cm^3) at −100 °C over a period of 3 min. After the reaction mixture was stirred for 2 min, a solution of acetaldehyde (25.2 cm^3, 1.17 mol cm^{-3} in THF, 29.5 mmol) was added. The reaction mixture was stirred for 15 min, then quenched with saturated aqueous NH_4Cl (10 cm^3), and concentrated under reduced pressure. The aqueous mixture was extracted with CH_2Cl_2 (3 × 5 cm^3). The combined organic extracts were washed with brine (10 cm^3), dried over Na_2SO_4, and concentrated to give the crude alcohol, which was purified by column chromatography (silica gel, CH_2Cl_2–ethyl acetate, 60:40) to give the alcohol **6a** (1.14 g, 87%) as a mixture of four diastereomers composed mainly of the (*E*)-isomers. (*E*)-**6a** (Found: C, 64.28; H, 7.30. $C_{12}H_{16}O_2S$ requires C, 64.25; H, 7.19%); TLC R_f = 0.17 (hexane–ethyl acetate, 50:50); ν_{max}(neat)/cm^{-1} 3370, 2980, 1600, 1495, 1450, 1400, 1380, 1080 and 1030; δ_H 1.07 and 1.22 [3 H, 2 × d, *J* 6.7 and 6.8, CH(OH)CH_3], 1.98 (3 H, d, *J* 7.2, CH_3CH=C), 2.41 (3 H, s, ArCH_3), 2.70–2.84 (1 H, m, OH), 4.61–4.85 [1 H, m, C*H*(OH)], 6.43 and 6.53 (1 H, 2 × q, *J* 7.2 and 7.2, CH=C), 7.22–7.37 (2 H, m, ArH) and 7.43–7.59 (2 H, m, ArH); *m*/*z* (EI) 224 (M^+, 12%), 206 (6) and 140 (100).

3-(4-Methoxyphenylsulfinyl)pent-3-en-2-ol 6b. The reaction was carried out as described above using the sulfoxide **5b** (1.20 g, 6.11 mmol) to give the alcohol **6b** (1.01 g, 69%) as a mixture of four diastereomers; TLC R_f = 0.17 (hexane–ethyl acetate, 30:70); ν_{max}(neat)/cm^{-1} 3370, 2975, 1595, 1500, 1250, 1090 and 1025; δ_H 1.01–1.46 [3 H, m, CH(OH)CH_3], 1.89–2.22 (3 H, m, CH_3CH=C), 2.56–292 (1 H, m, OH), 3.85 and 3.86 (3 H, 2 × s, OCH_3), 4.05–4.85 [1 H, m, C*H*(OH)], 6.23–6.62 (1 H, m, CH=C), 6.90–7.12 (2 H, m, ArH) and 7.39–7.67 (2 H, m, ArH); *m*/*z* (EI) 240 (M^+, 17%), 192 (9) and 156 (100).

3-(4-Chlorophenylsulfinyl)pent-3-en-2-ol 6c. The reaction was carried out as described above using the sulfoxide **5c** (1.20 g, 5.98 mmol) to give the alcohol **6c** (769 mg, 53%) as a mixture of four diastereomers; TLC R_f = 0.31 (hexane–ethyl acetate, 50:50); ν_{max}(neat)/cm^{-1} 3370, 2980, 1580, 1480, 1395, 1090 and 1030; δ_H 1.02–1.40 [3 H, m, CH(OH)CH_3], 1.90–2.24 (3 H, m, CH_3CH=C), 2.42–2.85 (1 H, m, OH), 4.40–4.92 [1 H, m, C*H*(OH)], 6.30–6.63 (1 H, m, CH=C) and 7.39–7.67 (4 H, m, ArH); *m*/*z* (EI) 244 (M^+, 13%), 226 (16) and 160 (100).

(S_S)-3-(2,4,6-Triisopropylphenylsulfinyl)pent-3-en-2-ol 6d. The reaction was carried out as described above using the sulfoxide **5d** (1.06 g, 3.62 mmol) to give the alcohol **6d** (1.11 g, 91%) as a diastereomeric mixture of (*E*)-isomers in a ratio of 57:43 (Found: C, 71.49; H, 9.71. $C_{20}H_{32}O_2S$ requires C, 71.38; H, 9.58%); TLC R_f = 0.26 (hexane–ethyl acetate, 70:30); ν_{max}(neat)/cm^{-1} 3315, 2970, 1600, 1460, 1370, 1110 and 1020; δ_H 1.05–1.34 [18 H, m, 3 × CH(CH_3)$_2$], 1.36 and 1.59 [3 H, 2 × d, *J* 6.5 and 6.7, CH(OH)CH_3], 1.81 and 1.87 (3 H, 2 × d, *J* 7.2 and 7.3, CH_3CH=C), 2.59 and 3.83 (1 H, 2 × d, *J* 7.1 and 7.8, OH), 2.76–3.03 [1 H, m, C*H*(CH_3)$_2$], 3.58–4.02 [2 H, m, 2 × C*H*(CH_3)$_2$], 4.61–5.06 [1 H, m, C*H*(OH)], 5.51 and 5.77 (1 H, 2 × q, *J* 7.2 and 7.3, CH=C) and 7.07 and 7.10 (2 H, 2 × s, ArH); *m*/*z* (EI) 336 (M^+, 3%), 318 (46), 301 (61), 275 (36) and 255 (100).

(*S*,*E*)-3-(*p*-Tolylsulfinyl)pent-3-en-2-one 7a.—*Method A via the Swern oxidation.*[7a] To a solution of oxalyl chloride (55.5 × 10^{-3} cm^3, 0.636 mmol) in CH_2Cl_2 (1 cm^3) was added dimethyl sulfoxide (60.2 × 10^{-3} cm^3, 0.848 mmol) at −78 °C. After the mixture was stirred for 5 min, a solution of the alcohol **6a** (95.1 mg, 0.424 mmol) in CH_2Cl_2 (0.8 cm^3) was added. The reaction mixture was stirred for an additional 1 h at −78 °C. Then triethylamine (0.12 cm^3, 0.848 mmol) was added to the reaction mixture, which was stirred for 5 min. The reaction mixture was poured into ice-cooled 1 mol dm^{-3} aqueous HCl (10 cm^3). The aqueous layer was extracted with CH_2Cl_2 (3 × 5 cm^3). The combined organic extracts were washed with ice–water (10 cm^3), dried over Na_2SO_4, and concentrated to give the crude enone, which was purified by column chromatography (hexane–ethyl acetate, 60:40) to give the enone **7a** (64.1 mg, 68%) as a mixture of two diastereomers.

Method B via the Jones oxidation.[8] To a solution of the alcohol **6a** (103 mg, 0.458 mmol) in acetone (3 cm^3) was added at 0 °C the Jones reagent [prepared from chromium(VI) oxide (9.99 g, 100 mmol), 97% sulfuric acid (11.0 cm^3, 200 mmol) and water (50 cm^3)], until the starting alcohol disappeared on TLC. The reaction mixture was quenched with water (3 cm^3) and concentrated under reduced pressure. The aqueous mixture was extracted with Et_2O. The combined organic extracts were washed with brine (5 cm^3), dried over Na_2SO_4, and concentrated to give the crude enone, which was purified by column chromatography (hexane–ethyl acetate, 60:40) to give the enone **7a** (86.5 mg, 85%) as a mixture of two diastereomers. The (*E*)-isomer was further purified by recrystallization from Et_2O (Found: C, 64.80; H, 6.46. $C_{12}H_{14}O_2S$ requires C, 64.84; H, 6.35%); TLC R_f = 0.24 (hexane–ethyl acetate, 60:40); mp 61–62 °C (from Et_2O); $[\alpha]_D^{22}$ +255 (*c* 0.434 in $CHCl_3$); ν_{max}(KBr)/cm^{-1} 2920, 1660, 1625, 1430, 1380, 1220 and 1050; δ_H 2.22 (3 H, d, *J* 7.4, CH_3CH), 2.24 (3 H, s, CH_3CO), 2.38 (3 H, s, ArCH_3), 7.05 (1 H, q, *J* 7.4, CH=C), 7.25 (2 H, d, *J* 8.3, ArH) and 7.52 (2 H, d, *J* 8.3, ArH); δ_C 15.7, 21.3, 31.4, 125.6, 129.8, 139.4, 140.1, 141.8, 146.2 and 195.9; *m*/*z* (EI) 222 (M^+, 29%), 149 (28), 140 (53) and 139 (100).

3-(4-Methoxyphenylsulfinyl)pent-3-en-2-one 7b. The reaction was carried out as described above (Method A) using the alcohol **6b** (700 mg, 2.91 mmol) to give the enone **7b** (399 mg, 58%). An *E*:*Z* = 72:28 mixture was used for the radical reaction, since attempts to isolate the (*E*)-isomer were unsuccessful (Found: C, 60.31; H, 5.89. $C_{12}H_{14}O_3S$ requires C, 60.48; H,

5.92%); TLC R_f = 0.51 (hexane–ethyl acetate, 50 : 50); ν_{max}(KBr)/cm^{-1} 2940, 1655, 1600, 1500, 1255 and 1040; δ_H 2.22 and 2.24 (3 H, 2 × s, CH_3CO), 2.24 and 2.38 (3 H, 2 × d, *J* 7.6 and 7.5, CH_3CH), 3.83 and 3.85 (3 H, 2 × s, OCH_3), 6.90–7.07 (2 H, m, ArH), 7.05 and 7.32 (3 H, 2 × q, *J* 7.6 and 7.5, CH=C) and 7.48–7.63 (2 H, m, ArH); *m*/*z* (EI) 238 (M$^+$, 51%), 190 (40) and 155 (100).

(*E*)-3-(4-Chlorophenylsulfinyl)pent-3-en-2-one 7c. The reaction was carried out as described above (Method A) using the alcohol **6c** (500 mg, 2.04 mmol) to give the enone **7c** (424 mg, 86%) (Found: C, 54.32; H, 4.51. $C_{11}H_{11}ClO_2S$ requires C, 54.43; H, 4.57%); TLC R_f = 0.29 (hexane–ethyl acetate, 50 : 50); ν_{max}(KBr)/cm^{-1} 3080, 2930, 1660, 1620, 1480, 1380, 1210 and 1050; δ_H 2.26 (3 H, d, *J* 7.6, CH_3CH), 2.31 (3 H, s, CH_3CO), 7.11 (1 H, q, *J* 7.6, CH=C) and 7.36–7.65 (4 H, m, ArH); δ_C 15.8, 31.5, 126.8, 129.3, 137.3, 140.2, 142.2, 146.1 and 195.6; *m*/*z* (EI) 242 (M$^+$, 51%), 183 (25), 144 (46) and 112 (100).

(*S*,*E*)-3-(2,4,6-Triisopropylphenylsulfinyl)pent-3-en-2-one 7d. The reaction was carried out as described above (Method B) using the alcohol **6d** (338 mg, 1.00 mmol) to give the enone **7d** (242 mg, 72%), which was further purified by recrystallization from Et_2O (Found: C, 71.65; H, 9.22. $C_{20}H_{30}O_2S$ requires C, 71.81; H, 9.04%); TLC R_f = 0.43 (hexane–ethyl acetate, 70 : 30); mp 70–71 °C (from Et_2O); $[\alpha]_D^{22}$ +286 (*c* 0.402 in $CHCl_3$); ν_{max}(KBr)/cm^{-1} 2970, 1675, 1600, 1470, 1375, 1190 and 1050; δ_H 1.20, 1.22 and 1.27 [18 H, 3 × d, *J* 6.9, 6.9, 6.9, 3 × CH(CH_3)$_2$], 2.17 (3 H, d, *J* 7.6, CH_3CH), 2.20 (3 H, s, CH_3CO), 2.73–3.00 [1 H, m, CH(CH$_3$)$_2$], 3.72–4.00 [2 H, m, 2 × CH(CH$_3$)$_2$], 6.77 (1 H, q, *J* 7.6, CH=C) and 7.03 (2 H, s, ArH); δ_C 15.7, 23.7, 25.0, 27.8, 31.3, 34.3, 123.1, 132.1, 135.8, 146.7, 151.3, 153.0 and 197.0; *m*/*z* (EI) 334 (M$^+$, 6%), 317 (4) and 291 (100).

General procedure for radical β-addition to α-(arylsulfinyl) enones 7

A solution of the α-(arlysulfinyl) enone **7** in CH_2Cl_2 (0.01 mol dm^{-3}) was degassed under reduced pressure using a sonicator. To this solution was added triethylborane (10 equiv.) and isopropyl iodide (10 equiv.) at 0 °C. In the reaction using an additive, the additive (1.1 equiv.) was added at 0 °C and the mixture was stirred for 1 h before the addition of triethylborane and isopropyl iodide. Then air was passed through the solution by a microfeeder at a rate of 90.0 × 10^{-3} cm^3 min^{-1} per 1 mmol of triethylborane. The reaction mixture was poured into saturated aqueous NaH_2PO_4, and extracted with Et_2O. The combined organic extracts were dried over Na_2SO_4 and concentrated to give the crude product which was purified by column chromatography to give the addition product **8** and the Pummerer-type product **9**.

4,5-Dimethyl-3-(*p*-tolylsulfinyl)hexan-2-one 8a. (Found: C, 67.47; H, 8.48. $C_{15}H_{22}O_2S$ requires C, 67.63; H, 8.32%); TLC R_f = 0.51 (hexane–ethyl acetate, 60 : 40); ν_{max}(neat)/cm^{-1} 2970, 1705, 1360, 1215 and 1060; δ_H 0.63–1.39 [9 H, m, CH(CH_3)$_2$ and CHCH_3], 1.81, 1.196 and 2.00 (3 H, 3 × s, CH_3CO), 2.17–2.70 [2 H, m, CH(CH$_3$)$_2$ and CHCH$_3$], 2.41 (3 H, s, ArCH_3), 3.13, 3.23, 3.93 and 3.95 (1 H, 4 × d, *J* 11.7, 11.0, 6.3 and 9.7, COCHSO) and 7.22–7.56 (4 H, m, ArH); *m*/*z* (EI) 266 (M$^+$, 1%), 140 (100) and 127 (70).

4,5-Dimethyl-3-(4-methoxyphenylsulfinyl)hexan-2-one 8b. (Found: C, 63.97; H, 7.92. $C_{15}H_{22}O_3S$ requires C, 63.80; H, 7.85%); TLC R_f = 0.53 (hexane–ethyl acetate, 50 : 50); ν_{max}(neat)/cm^{-1} 2960, 1700, 1600, 1500, 1360, 1090 and 1055; δ_H 0.65–1.34 [9 H, m, CH(CH_3)$_2$ and CHCH_3], 1.95 and 2.02 (3 H, 2 × s, CH_3CO), 2.17–2.68 [2 H, m, CH(CH$_3$)$_2$ and CHCH$_3$], 3.13 and 3.26 (1 H, 2 × d, *J* 11.8 and 10.8, COCHSO) and 3.73–3.90 (1 H, m, COCHSO), 3.84 and 3.85 (3 H, 2 × s, OCH_3), 6.96–7.10 (2 H, m, ArH) and 7.37–7.51 (2 H, m, ArH); *m*/*z* (EI) 282 (M$^+$, 20%), 156 (81) and 155 (100).

4,5-Dimethyl-3-(4-chlorophenylsulfinyl)hexan-2-one 8c. (Found: C, 58.48; H, 6.56. $C_{14}H_{19}ClO_2S$ requires C, 58.63; H, 6.68%); TLC R_f = 0.65 (hexane–ethyl acetate, 50 : 50); ν_{max}(neat)/cm^{-1} 2970, 1705, 1480, 1395, 1360, 1280 and 1050; δ_H 0.72–1.39 [9 H, m, CH(CH_3)$_2$ and CHCH_3], 1.87, 1.96, 1.99 and 2.00 (3 H, 4 × s, CH_3CO), 1.50–2.70 [2 H, m, CH(CH$_3$)$_2$ and CHCH$_3$], 3.13, 3.23, 3.94 and 3.99 (1 H, 4 × d, *J* 12.3, 11.0, 6.5 and 9.5, COCHSO) and 7.37–7.62 (4 H, m, ArH); *m*/*z* (EI) 286 (M$^+$, 3%), 217 (5), 202 (8), 160 (100) and 127 (92).

4,5-Dimethyl-3-(*p*-tolylsulfanyl)hex-3-en-2-one 9a. (Found: C, 72.55; H, 8.17. $C_{15}H_{20}OS$ requires C, 72.54; H, 8.12%); TLC R_f = 0.80 (hexane–ethyl acetate, 60 : 40); ν_{max}(neat)/cm^{-1} 2970, 1730, 1690, 1490 and 1270; δ_H 1.06 and 1.08 [6 H, 2 × d, *J* 6.8 and 6.8, CH(CH_3)$_2$], 1.91 and 1.98 (3 H, 2 × s, CH_3C=), 2.23 and 2.24 (3 H, 2 × s, CH_3CO), 2.28 (3 H, s, ArCH_3), 2.92–3.03 and 3.43–3.64 [1 H, 2 × m, CH(CH$_3$)$_2$] and 7.07 (4 H, s, ArH); *m*/*z* (EI) 248 (M$^+$, 100%), 233 (16) and 137 (33).

4,5-Dimethyl-3-(4-methoxyphenylsulfanyl)hex-3-en-2-one 9b. (Found: C, 68.17; H, 7.48. $C_{15}H_{20}O_2S$ requires C, 68.15; H, 7.62%); TLC R_f = 0.88 (hexane–ethyl acetate, 50 : 50); ν_{max}(neat)/cm^{-1} 2960, 1690, 1600, 1500, 1295 and 1245; δ_H 1.06 and 1.07 [6 H, 2 × d, *J* 6.9 and 6.8, CH(CH_3)$_2$], 1.87 and 1.98 (3 H, 2 × s, CH_3C=), 2.22 and 2.23 (3 H, 2 × s, CH_3CO), 2.85–3.05 and 3.45–3.68 [1 H, 2 × m, CH(CH$_3$)$_2$], 3.77 (3 H, s, OCH_3), 6.82–6.90 (2 H, m, ArH) and 7.10–7.22 (2 H, m, ArH); *m*/*z* (EI) 264 (M$^+$, 100%), 250 (10), 151 (28), 140 (50) and 113 (75).

4,5-Dimethyl-3-(4-chlorophenylsulfanyl)hex-3-en-2-one 9c. (Found: C, 62.66; H, 6.39. $C_{14}H_{17}ClOS$ requires C, 62.56; H, 6.37%); TLC R_f = 0.85 (hexane–ethyl acetate, 50 : 50); ν_{max}(neat)/cm^{-1} 2970, 1690, 1480, 1350, 1205 and 1100; δ_H 1.03 and 1.07 [6 H, 2 × d, *J* 6.8 and 6.8, CH(CH_3)$_2$], 1.91 and 1.95 (3 H, 2 × s, CH_3C=), 2.23 (3 H, s, CH_3CO), 2.90–3.14 and 3.30–3.57 [1 H, 2 × m, CH(CH$_3$)$_2$] and 7.00–7.25 (4 H, m, ArH); *m*/*z* (EI) 268 (M$^+$, 100%), 254 (20), 225 (12), 155 (24), 143 (13) and 125 (20).

4,5-Dimethyl-3-(2,4,6-triisopropylphenylsulfanyl)hex-3-en-2-one 9d. (Found: C, 76.55; H, 10.20. $C_{23}H_{36}OS$ requires C, 76.61; H, 10.06%); TLC R_f = 0.72 (hexane–ethyl acetate, 80 : 20); ν_{max}(neat)/cm^{-1} 2970, 1700, 1600, 1470, 1370 and 1205; δ_H 1.02 and 1.09 [6 H, 2 × d, *J* 6.8 and 6.8, CH(CH_3)$_2$], 1.13–1.69 [21 H, m, 3 × CH(CH_3)$_2$ and CH_3C=], 1.91 and 1.97 (3 H, 2 × s, CH_3CO), 2.50–2.73 and 3.48–3.75 [1 H, 2 × m, CH(CH$_3$)$_2$], 2.72–2.98 [1 H, m, CH(CH$_3$)$_2$], 3.53–3.82 [2 H, m, 2 × CH(CH$_3$)$_2$] and 6.96 (2 H, s, ArH); *m*/*z* (EI) 360 (M$^+$, 52%), 317 (7), 204 (100) and 189 (67).

5-Methyl-3-(*p*-tolylsulfinyl)hexan-2-one 11. (Found: C, 66.52; H, 7.91. $C_{14}H_{20}O_2S$ requires C, 66.63; H, 7.99%); TLC R_f = 0.17 (hexane–ethyl acetate, 80 : 20); HPLC t_R = 29.02, 31.70, 33.18 and 37.44 min (hexane–propan-2-ol, 98 : 2); ν_{max}(neat)/cm^{-1} 2960, 1710, 1680, 1625, 1580, 1355, 1290, 1170 and 1040; δ_H 0.80–1.00 [6 H, m, CH(CH_3)$_2$], 1.15–1.41 (2 H, m, CH$_2$), 1.49–1.75 [1 H, m, CH(CH$_3$)$_2$], 1.90, 2.16 (3 H, 2 × s, CH_3CO), 2.42 (3 H, s, ArCH_3), 3.54 and 3.76 (1 H, 2 × dd, *J* 5.4, 9.8 and 4.4, 9.6, COCHSO) and 7.27–7.53 (4 H, m, ArH); *m*/*z* (EI) 252 (M$^+$, 5%), 201 (3), 140 (100) and 139 (89).

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