Allylation of Aldehyde and Imine Substrates with In Situ Generated Allylboronates – A Simple Route to Enatioenriched Homoallyl Alcohols

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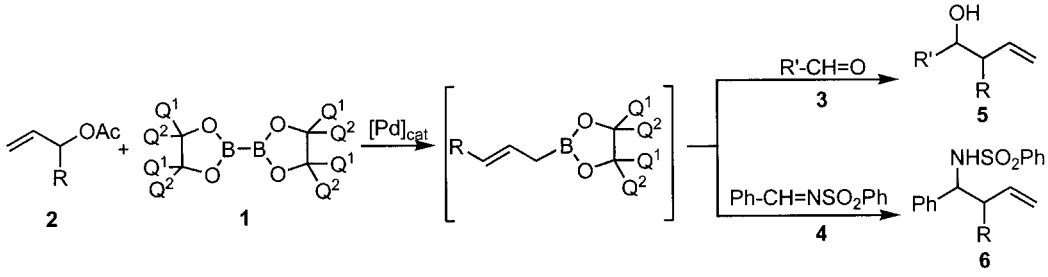
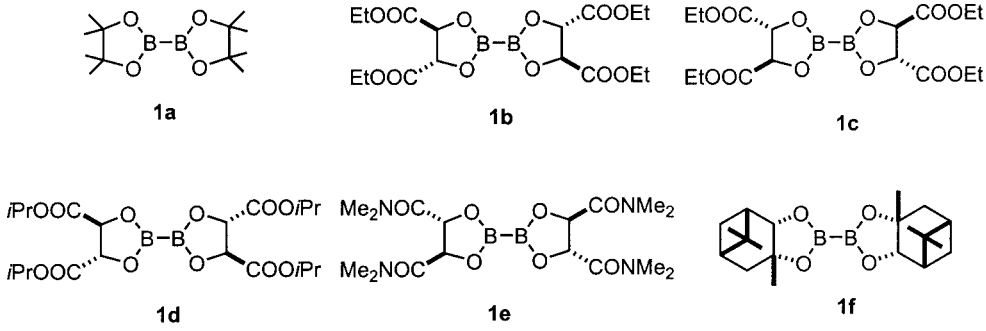
Allylation of aldehyde and imine substrates was achieved using easily available allylacetates and diboronate reagents in the presence of catalytic amounts of palladium. This operationally simple one-pot reaction has a broad synthetic scope, as many functionalities including, acetate, carbethoxy, amido and nitro groups are tolerated. The allylation reactions proceed with excellent regio- and stereoselectivity affording the branched allylic isomer. By employment of commercially available chiral diboronates enantioenriched homoallyl alcohols (up to 53 % *ee*) could be obtained. The mechanistic studies revealed that the in situ generated allylboronates react directly with the aldehyde substrates, however the allylation of the sulfonylimine substrate requires palladium catalysis.

Introduction

The reactions of allylboronates with aldehyde and other electrophiles offer an attractive approach for synthesis of regio- and stereodefined products.[1–5] Furthermore, tartrate based chiral allylboronates react with aldehydes with good to high level of enantioselectivity.[4,6,7] Although, the parent allylboronate and its alkyl-substituted analogs are easily available reagents, the limited access to properly functionalized and/or chiral allylboronates often limit the synthetic scope of the allylation reactions. Recently, we have communicated[8] an efficient one-pot allylation procedure based on in situ generation of allylboronates (Scheme 1). In this procedure the transient allylboronates were prepared by a pal-



Scheme 1. One-pot allylation of aldehyde **3** and imine **4** substrates through palladium-catalyzed formation of transient allylboronates.



Scheme 2. Various diboronates employed in this study.

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ladium-catalyzed process from bis(pinacolato)diboron (**1a**) (Scheme 2) and easily available functionalized allylacetates **2a**–**g**. Using this procedure the electrophiles nitrobenzaldehyde **3a** and sulfonylimine **4** were allylated with a high regio- and stereoselectivity affording the homoallyl alcohols **5a**–**g** and amines **6a**–**d** as products. In this paper we give a full account of our results on these types of reactions. In addition, we present our new results on some important synthetic and mechanistic aspects of this reaction: (i) Possibilities to extend the synthetic scope of the reaction to nonactivated aldehydes **3b** and **3c**; and (ii) application of the chiral diboronate reagents **1b**–**f** to prepare enantiomerically enriched homoallyl alcohols.

Results and Discussion

Allylation of Aldehyde and Imine Electrophiles

As we communicated before,[8] the reaction conditions of the palladium-catalyzed boronation of the allylacetates **2** are fully compatible with the electrophilic substitution of

Table 1. Allylation of aldehyde and imine electrophiles by catalytically generated allylboronates.

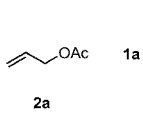
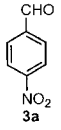
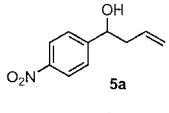
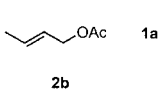
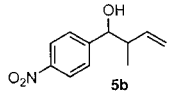
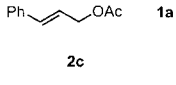
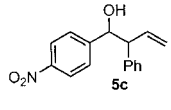
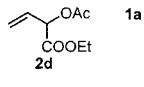
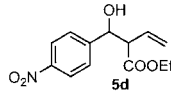
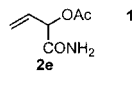
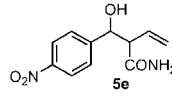
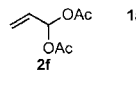
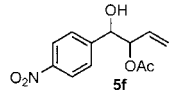
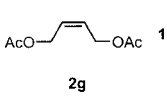
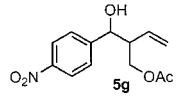
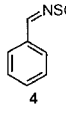
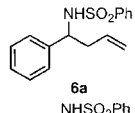
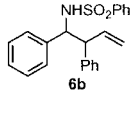
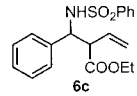
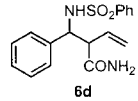
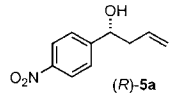
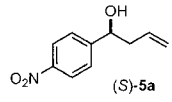
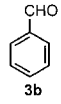
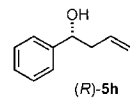
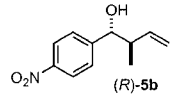
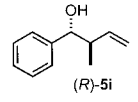
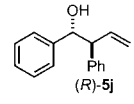
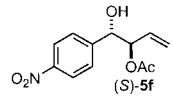
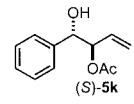
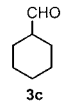
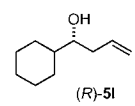
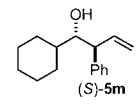
Entry	Allyl	Boronate	Electrophile	Method[a]	Product	*dr*[b]	*ee*[c]	Yield[d]
1	 **2a**	**1a**	 **3a**	20/21	 **5a**	–	–	73
2	 **2b**	**1a**	**3a**	60/21	 **5b**	ao	–	81
3	 **2c**	**1a**	**3a**	40/21	 **5c**	33:1	–	86
4	 **2d**	**1a**	**3a**	20/24	 **5d**	8:1	–	75
5	 **2e**	**1a**	**3a**	20/21	 **5e**	8:1	–	61
6	 **2f**	**1a**	**3a**	20/91	 **5f**	ao	–	74
7	 **2g**	**1a**	**3a**	20/93	 **5g**	ao	–	69
8	**2a**	**1a**	 **4**	60/4	 **6a**	–	–	80
9	**2c**	**1a**	**4**	20/69	 **6b**	so	–	91

Table 1. *(continued)*.

Entry	Allyl	Boronate	Electrophile	Method[a]	Product	*dr*[b]	*ee*[c]	Yield[d]
10	**2d**	**1a**	**4**	20/21	 **6c**	1:11	–	55
11	**2e**	**1a**	**4**	20/21	 **6d**	1:6	–	75
12	**2a**	**1b**	**3a**	20/19	 (*R*)-**5a**	–	53	83
13	**2a**	**1b**	**3a**	20/20[e]	(*R*)-**5a**	–	51	69
14	**2a**	**1c**	**3a**	20/22	 (*S*)-**5a**	–	49	92
15	**2a**	**1d**	**3a**	20/20	(*R*)-**5a**	–	45	76
16	**2a**	**1e**	**3a**	20/21	(*S*)-**5a**	–	3	73
17	**2a**	**1f**	**3a**	20/21	(*R*)-**5a**	–	1	62
18	**2a**	**1b**	 **3b**	20/63	 (*R*)-**5h**	–	45	83
19	**2a**	**1d**	**3b**	20/44	(*R*)-**5h**	–	42	63
20	**2b**	**1b**	**3a**	20/93	 (*R*)-**5b**	ao	34	64
21	**2b**	**1b**	**3b**	20/96	 (*R*)-**5i**	ao	33	76
22	**2c**	**1b**	**3b**	20/21	 (*R*)-**5j**	ao	43	83
23	**2f**	**1b**	**3a**	20/21	 (*S*)-**5f**	ao	50	67
24	**2f**	**1b**	**3b**	20/21	 (*S*)-**5k**	ao	45	59
25	**2a**	**1b**	 **3c**	40/66	 (*R*)-**5l**	–	48	58
26	**2c**	**1b**	**3c**	20/69	 (*S*)-**5m**	ao	53	77
27	**2a**	**1b**	**4**	20/25	**6a**	ao	0	52

[a] The reactions with were conducted in DMSO (for **1a**) or DMSO/toluene, 1:1 (for **1b**–**f**) using 6 mol-% Pd catalyst at given the temperature/reaction time [hours]/[°C]. [b] Diastereomer ratio (*dr*) (*anti*/*syn*); ao = *anti* isomer only; so = *syn* isomer only. [c] Enantiomeric excess. The major enantiomer is depicted in the product column. [d] Isolated yield. [e] In DMSO solvent.

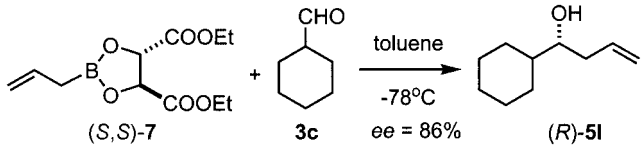
the transient allylboronates with aldehyde and imine electrophiles. In a typical reaction the diboronate **1**, the allylacetate **2**, the appropriate electrophile (**3** or **4**) and catalytic amounts of $Pd_2(dba)_3$ [dba = (dibenzylidene)acetone] were mixed in DMSO and after the allotted reaction time (Table 1) the corresponding product (**5** or **6**) was isolated. Using **1a** as diboronate reagent the typical reaction temperature was room temperature or 40 °C, however the crotyl substrate (Entry 2) required a somewhat higher reaction temperature (60 °C). The broad synthetic scope is a particularly important feature of this reaction. Many functionalities, such as NO_2, COOEt, $CONH_2$ and OAc (Entries 4–7), are tolerated under the applied reaction conditions. The reactions involving substituted allylacetates provide the branched products with very high regioselectivity. The diastereoselectivity of the reaction is also very high. In many cases a single diastereomer was obtained (Entries 2, 6, 7 and 9), while in the rest of the reactions one of the diastereomers dominated of the products. It was found that the aldehyde electrophile **3a** reacted with *anti* diastereoselectivity (Entries 2–7), while the imine substrate **4** gave exclusively or predominantly *syn* product (Entries 9–11).

We have found that the best solvent for the reaction was DMSO. In other solvents, such as THF, acetonitrile, benzene or toluene, black palladium(0) was precipitated immediately after addition of the allylacetate component. On the other hand, we were not able to stabilize the palladium(0) catalyst in these solvents by addition of phosphanes [e.g. PPh_3, $P(OPh)_3$] or activated alkenes (e.g. maleic anhydride and COD), as these additives strongly inhibited the catalytic process. Other strongly coordinating ligands, such as halide salts also retarded or completely inhibited the catalytic formation of the transient allylboranes. Therefore, employment of $Pd_2(dba)_3$ as catalyst source and DMSO as solvent or co-solvent (vide infra) seems to be indispensable for the catalytic generation of allylboronates from diboronate precursors.

Application of Chiral Diboronates 1b–f

The high regio- and diastereoselectivity of the reaction inspired us to conduct the reaction (Scheme 1) in the presence of the commercially available chiral diboronates **1b**–**f** in place of **1a**. We have found that tartrate-based diboronates **1b**–**d** reacted with the allylacetate **2a** and nitrobenzaldehyde (**3a**) to give homoallyl alcohol **5a** up to 53% *ee* (Table 1). Using D-tartrate derivatives (**1b** or **1d**, Entries 12, 13 and 15) with **3a** the major product was the *R*-enantiomer [(*R*)-**5a**]. As expected, the enantioselectivity of the reaction is reversed using L-tartrate derivative **1c** with **3a** providing (*S*)-**5a** with 48% *ee* (Entry 14). Tartaramide derivative **1e** and pinane derivative **1f** are ineffective in chiral induction giving a nearly racemic product (Entries 16 and 17). Although ethyl ester **1b** is expected[4] to give less stable allylboronates than the isopropyl ester **1d**, we obtained somewhat higher *ee* with **1b** than **1d**; and moreover, **1b** is less expensive than **1d**. Therefore, we employed chiral diboronate **1b** in the further studies. According to Roush and co-workers[4] the highest *ee* with chiral allylboronates can be achieved in toluene solvent. Therefore, we conducted the asymmetric allylation reactions in the presence of toluene co-solvent (in toluene/DMSO, 1:1). In fact, conducting the reactions in toluene/DMSO mixture gives higher *ee* and isolated yield of the product than the same process in neat DMSO (c.f. Entries 12 and 13).

We have found that employment of chiral tartrate derivative **1b** in place of **1a** leads to a higher reactivity, and therefore to a faster reaction. Thus the allylation reactions could also be performed under mild reaction conditions using benzaldehyde (**3b**) and aliphatic aldehyde **3c**. The reaction with benzaldehyde (**3b**) gave predominantly (*R*)-**5h** with lower enantioselectivity (Entry 18, 45% *ee*) than the corresponding reaction with nitrobenzaldehyde **3a** (Entry 12, 53% *ee*). The reaction with cyclohexanecarbaldehyde (**3c**) (Entry 25) requires an extended reaction time to give (*R*)-**5l** (48% *ee*). It is interesting to note that Roush and co-workers[4] obtained the same enantiopreference with chiral allylboronate (*S*,*S*)-**7** and **3c** (Scheme 3).



Scheme 3. Reaction of isolated chiral allylboronate (*S*,*S*)-**7** with **3c** reported by Roush and co-workers.[4]

We have also studied the reactions of functionalized allylacetates **2b**–**f** with chiral diboronate **1b** and aldehydes **3a**–**c**. The high regio- and stereoselectivity of the allylation reactions is maintained for each allylacetates, and accordingly the allylation reactions provided the corresponding branched product with *anti* diastereoselectivity (Entries 20–24 and 26). The increased reactivity provided by the tartrate derivative **1b** allowed lowering of the reaction temperature to room temp. using crotylacetate as substrate (c.f Entries 2 and 20). Allylation with crotyl and cinnamylacetate (**2b** and **2c**, Entries 20–22) proceeds with lower enantioselectivity (33–43% *ee*) than the corresponding process with the parent compound **2a** (53% *ee*, Entry 12). Increase of the polarity of the allylic substituent seems to improve the enantioselection. As one goes from crotylacetate (**2b**) through cinnamylacetate (**2c**) to the diacetate **2f** the *ee* increases from 34% to 50% (c.f. Entries 20–24). Thus, using diacetate **2f** and **3a** the reaction provided allylacetate (*S*)-**5f** with excellent regio- and stereochemistry and with 50% *ee* (Entry 23). It was also found that cyclohexanecarbaldehyde (**3c**) is allylated with a higher enantioselectivity than benzaldehyde (**3a**) (c.f. Entries 22 and 26).

The enantioselectivity of the allylation of the aldehydes **3a**–**c** is apparently lower with in situ generated allylboronates than with isolated ones. Roush and co-workers[4,9] have shown that allylation of **3b** and **3c** with (*S*,*S*)-**7** (or its enantiomer) can be achieved with 71% and 86% *ee* (Scheme 3) at –78 °C in toluene. An obvious drawback of

the presented reactions is that they are conducted at room temp. in presence of DMSO cosolvent. Probably the relatively high reaction temperature (required for the catalytic generation of allylboronates) is responsible for the lowering of the enantioselectivity of the process. Conducting the allylation of **3b** with isolated chiral allylboronate at room temp. (23 °C/CH_2Cl_2) the enantiomeric excess drops to 30%,[9] which is in the same range as the analog reaction with in situ generated allylboronate (Entry 18) giving 45% *ee*.

As it appears above, aldehydes **3a**–**c** give about 35–53% *ee* with **1b** and various allylacetates (**2a**–**c** and **2f**) in the presence of catalytic amounts of palladium. However, the reaction of the sulfonylimine **4** with **2a** and **1b** under the same catalytic condition gave racemic product (Entry 27). The lack of the enantioselectivity in this process indicates different mechanistic features for allylation of aldehyde and imine electrophiles.

Mechanistic Considerations

Palladium-catalyzed coupling of allylacetates with **1a** to give allylboronates was first reported by Miyaura and coworkers.[10] These authors also found that in these processes a considerable amount of 1,5-hexadiene derivatives were also formed (Scheme 4).

Formation of the transient allylboronate is also the introducing step of the one-pot allylation reaction described above (Scheme 1). However, in the one-pot process we did not observe formation of hexadiene products (such as **8**), since the allylboronate formed in the palladium-catalyzed process immediately react with the added electrophile. Interestingly, we have found that in the palladium-catalyzed reaction of **1a** and **2a** the consumption of the allylacetate (**2a**) is faster in the presence of the electrophile **3a** than in the absence of it (Figure 1). The retardation effect induced by the accumulation of the allylboronate product is even more pronounced when chiral diboronate **1b** is employed. When **2a** was reacted with **1b** in the presence of palladium catalyst, only 30% of **2a** was converted in 20 hours at room temp. to (*S*,*S*)-**7** (Scheme 5). On the other hand, conducting this reaction in the presence of nitrobenzaldehyde (**3a**) under the same reaction conditions (Entry 12) a full conversion of **2a** was observed. It should also be noted that formation of (*S*,*S*)-**7** in the previous reaction (Scheme 5) could be observed by ^{1}H NMR spectroscopy, however isolation of this allylboronate was encumbered by its low stability.

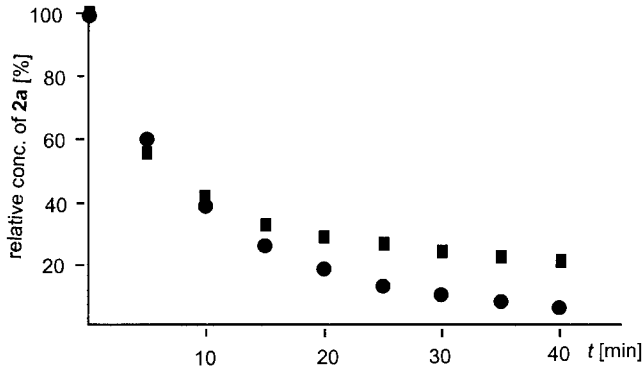
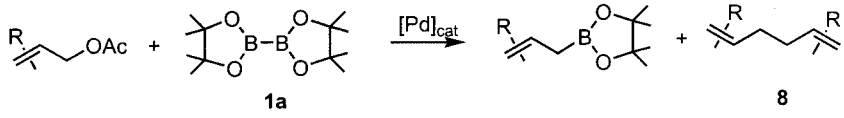


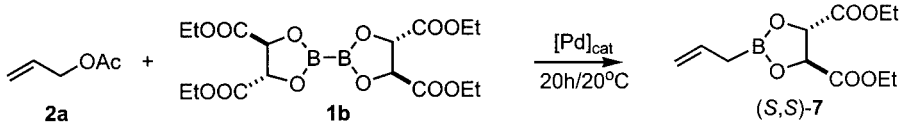
Figure 1. Palladium-catalyzed reaction of **2a** with **1a** in the presence (closed circles) and in the absence (closed square) of electrophile **3a**. The reactions were performed in [D_6]DMSO using identical amounts of $Pd_2(dba)_3$ catalyst. The progress of the reaction was followed by ^{1}H NMR spectroscopy.

The product inhibition in the above catalytic processes (Figure 1 and Scheme 5) can be explained by formation of bis(allyl)palladium complex **10** (Scheme 6) from the allylboronate product and the mono-allylpalladium intermediate of the process (**9**). Similar reactions for formation of bis(allyl)palladium complexes from (η^3-allyl)palladium complexes and allylstannanes are well documented in the literature.[11–19] Bis(allyl)palladium complexes such as **10b** are well known to undergo allyl–allyl coupling reactions to give hexadiene products,[11,12,20–22] which also explain the formation of **8** in the palladium-catalyzed boronation reaction in the absence of electrophiles (Scheme 4).

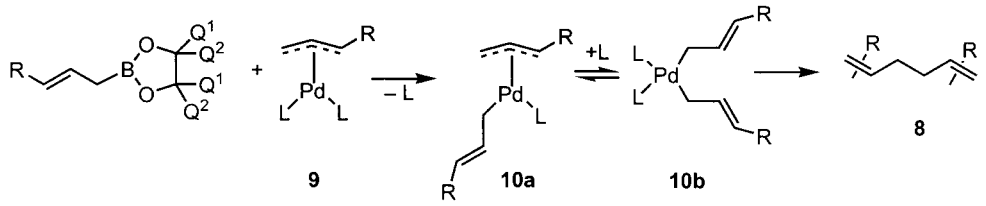
On the other hand, bis(allyl)palladium complexes **10** are also prone to react with electrophiles, such as aldehydes and imines.[13–19,22–25] In order to study the involvement of the palladium catalyses in the allylation step of the above reaction (Scheme 1), we reacted allylboronate **11** with nitrobenzaldehyde **3a** and imine **4** under the usual reaction conditions but in the absence of palladium catalyst (Scheme 7). The reaction of **3a** with **11** gave smoothly **5a**, clearly showing that the allylation of the aldehyde compo-



Scheme 4. Palladium-catalyzed boronation of allylacetates[10] in the absence of electrophiles.



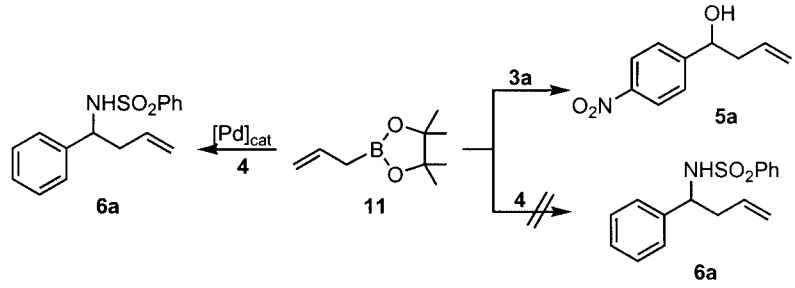
Scheme 5. Conducting this reaction in the *absence* of electrophile only 30% conversion of allylacetate **2a** could be achieved (c.f. Entry 12).



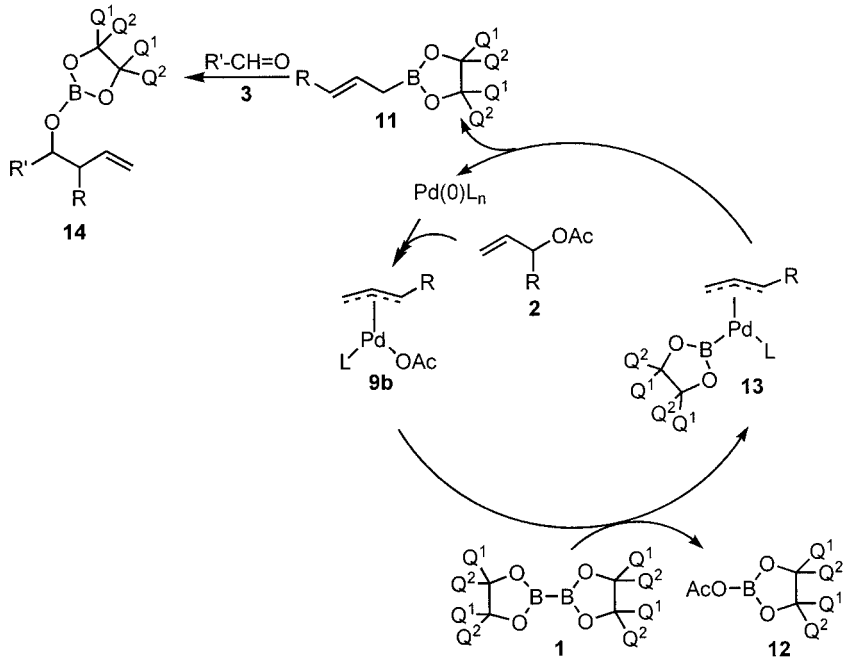
Scheme 6. Possible explanation of the product inhibition in the palladium-catalyzed formation of allylboronates.

nent does not require palladium catalysis. On the contrary, reaction of **4** with **11** does not provide the expected product **6a** unless catalytic amount of palladium is added to the reaction mixture. This latter experiment indicates that the allylation reaction of imine **4** requires palladium catalysis, and that this reaction proceeds via bis(allyl)palladium complex **10a**.

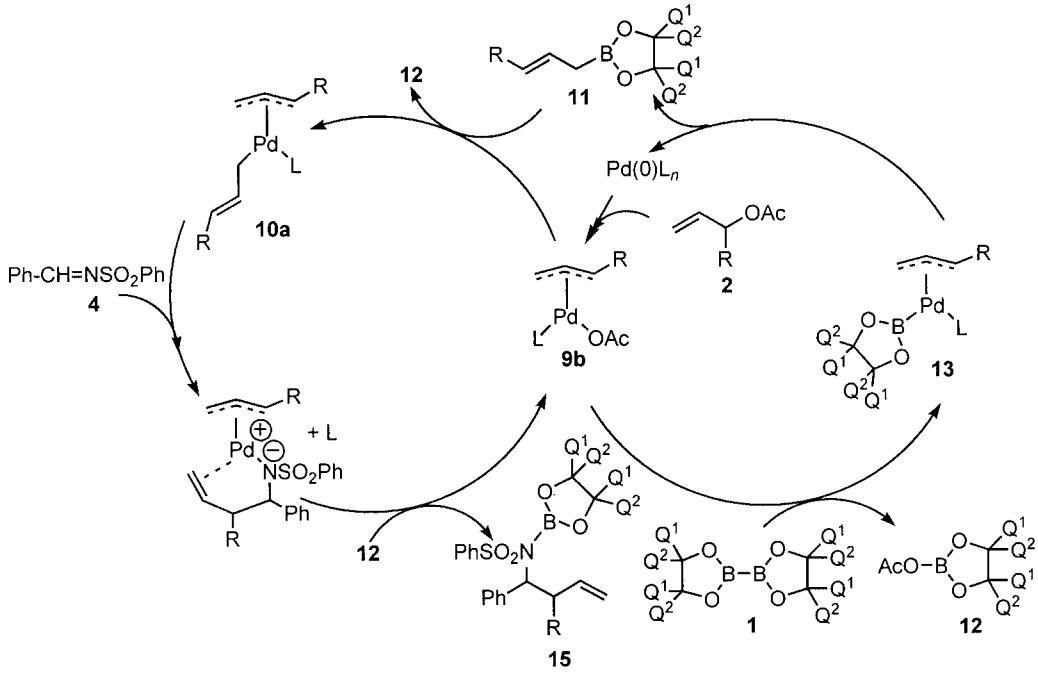
Considering the above findings two different catalytic cycles can be envisaged for the allylation of the aldehyde **3** and the imine substrate **4**. The introducing step for allylation of aldehydes **3a**–**c** (Scheme 8) is oxidative addition of the palladium(0) catalyst to the corresponding allylacetate to form (η^3-allyl)palladium complex **9b**.[26,27] The next step is addition of the diboron reagent to the allyl moiety of **9b** to form the transient allylboronate **11**. Considering these type of reactions with analog dimetal reagents,[10,17–19,28–30] such as hexaalkyl/aryldisilanes ($R_3Si–SiR_3$) and distannanes ($R_3Sn–SnR_3$) the boron–carbon bond formation probably takes place by a inner-sphere nucleophilic attack. Thus the nucleophilic attack is preceded by formation of complex **13**, in which the boronate group is coordinated to palladium. Coordination of the boronate group to palladium involves ligand exchange, which is certainly hindered in the presence of strongly coordinating ligands, such as phosphanes, acti-



Scheme 7. Allylation of aldehyde **3a** and imine **4** in the presence and absence of palladium catalyst.



Scheme 8. Catalytic cycle for the allylation of aldehydes **3a**–**c**.



Scheme 9. Catalytic cycle for the allylation of sulfonylimine **4**.

vated alkens or halogenides. This would explain our findings that the addition of strongly coordinating species (vide supra) inhibit the catalytic formation of the allylboronates **11**. On the other hand, in the absence of phosphane and other ligands DMSO is the only solvent, which is able to stabilize the palladium(0) catalyst source. The final step in the catalytic cycle is the direct attack of the aldehyde electrophile on the boronate **11** (Scheme 7) to give **14**, which subsequently hydrolyses to the homoallyl alcohol product.

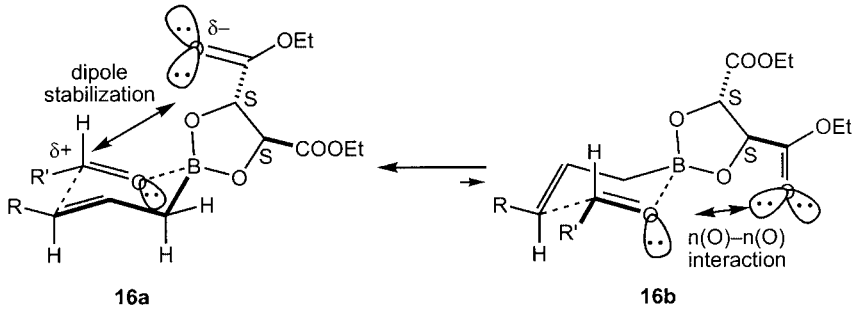
The allylation of imine **4** substrates also starts with palladium-catalyzed formation of the allylboronate **11**. In contrast to aldehyde **3,** imine **4** is not able to undergo direct electrophilic substitution with **11** (Scheme 7), and therefore the allylation step requires palladium catalysis. The second catalytic cycle (Scheme 9) is assumed to start with transmetallation of **11** to **9b** providing the bis(allyl)palladium complex **10a**. This complex undergoes electrophilic attack with imine **4** to give compound **15**. Similar reactions have been reported for palladium-catalyzed allylation of **4** with allyl stannane substrates.[17–19]

Development of the Selectivity

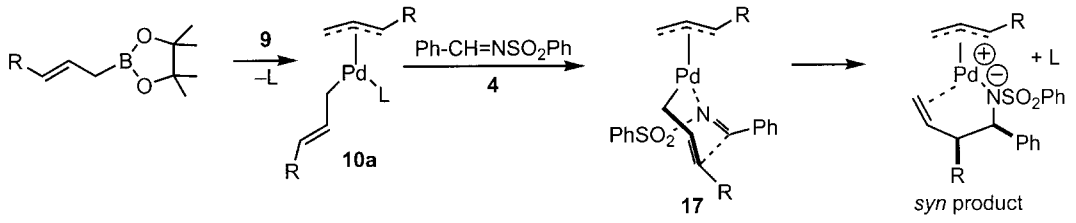
Probably the most important step of the catalytic process is the electrophilic attack on the allylmetal moiety, since this step determines the selectivity of the allylation process. The stereo- and enantioselectivity of the electrophilic attack on the aldehyde **3** and the imine **4** substrates is markedly different, which can be ascribed to the different reaction mechanism.

The direct attack on the aldehyde substrate **3** is known to proceed with a high *anti* diastereoselectivity.[1] The explanation of this diastereoselectivity is based on the assumption that the reaction takes place via six-membered cyclic TS (Scheme 10), in which substituents R and R′ occupy equatorial positions. This arrangement of the substituents in the TS leads to formations of the *anti* product, which explains the *anti* diastereoselectivity of the allylation reactions with aldehyde electrophiles.

The predominant formation of the *R* enantiomer from the transient (*S*,*S*)-**7** and the corresponding aldehydes **3a**–**c**



Scheme 10. Assumed TS structures in the selectivity determining step of the allylation of aldehydes.



Scheme 11. Evolution of the steroechemistry in the allylation of sulfonylimine **4**.

can be explained by the selectivity model presented by Roush and co-workers.[9,31,32] According to this model (Scheme 10) TS structure **16a** is stabilized by attractive interactions between the aldehyde carbonyl carbon (δ+) and the ester carbonyl oxygen (δ–).[31,32] On the other hand, **16b** is destabilized by four-electron interactions induced by the close proximity of the lone-pair electrons in the aldehyde carbonyl and in one of the ester carbonyls of the tartrate functionality. Considering these interactions TS **16a** is favored, and therefore the allylation reaction gives predominantly to the *R* enantiomer.

The reaction of **2a**, chiral diboronate **1b** and sulfonylimine **4** leads to the racemic homoallylamine **6a** (Entry 27). Formation of the racemic product is the consequence of the palladium-catalyzed allylation of imine **4** with transient allylboronate (*S*,*S*)-**7**. This reaction proceeds via the bis(allyl)palladium complex **10a** (Scheme 9) with a complete loss of the chiral information. Another interesting feature of the allylation of **4** is that this reaction takes place with *syn* diastereoselectivity, while the analog reaction with aldehydes **3a**–**c** proceeds with *anti* diastereoselectivity. Our recent studies[19] on the electrophilic substitution reactions via bis(allyl)palladium complexes have shown that the electrophilic attack in these processes also proceed through six-membered cyclic TS. Accordingly, the development of the stereoselectivity in the reaction of sulfonylimine **4** with allyl-substituted substrates **2c**–**e** (Entries 9–11) can be discussed on the basis of a six-membered TS structure model **17** (Scheme 11). The geometry of the TS structure **17** is biased by the *trans* geometry of the phenylsulphonyl and phenyl groups across the carbon–nitrogen double bond in **4**. Because of this *trans* geometry, the lone-pair on nitrogen (interacting with palladium) and the phenyl group are in a *cis* arrangement. Furthermore, it is reasonable to assume that the steric interactions between the metal atom and the bulky phenylsulfonyl group will be avoided. As a consequence, the preferred orientation of **4** in TS structure **17** renders the phenyl group to an axial position. Since the allylic substituent (R) is in an equatorial position, this model predicts formation of the *syn* diastereomer (Scheme 11). It is interesting to note that a similar *syn* diastereoselectivity was reported by Chan[33] and Lu for formation of **6b** in the indium- and zinc-mediated coupling of **4** with cinnamyl bromide.

Conclusions

Aldehyde **3** and imine **4** substrates can be allylated with allylacetates **2** in the presence of diboronates and catalytic amounts of palladium. Using this operationally simple one-pot synthesis the tedious isolation of unstable allylboronates can be avoided. The reactions proceed with an excellent regio- and stereoselectivity providing the branched allylic isomer. The allylation reaction with aldehydes **3** proceeds with *anti* diastereoselectivity, while the corresponding reaction with sulfonylimine substrate **4** takes place with *syn* diastereoselectivity. By employment of chiral diboronates **1b**–**d** enatiomerically enriched homoallyl alcohols (up to 53% *ee*) can be obtained using aldehyde electrophiles. Allylation of sulfonylimine **4** with allylacetates in the presence of chiral diboronates leads to racemic products. The mechanistic studies have shown that under the applied reaction conditions the aldehydes **3** react directly with the transient allylboronates, while the allylation of sulfonylimine **4** requires palladium catalysis. This latter reaction is assumed to proceed via the bis(allyl)palladium intermediates **10**. The stereo- and enantioselectivity of the reaction can be explained invoking six-membered cyclic TS structures (Scheme 10 and Scheme 11). Since the presented operationally simple one-pot reaction has a broad synthetic scope, high regio- and stereoselectivity and a promising enantioselectivity, it can be employed for selective synthesis of functionalized homoallyl alcohols.

Experimental Section

All reactions were conducted under argon employing standard manifold techniques. The ^{1}H NMR and ^{13}C NMR spectra were recorded in $CDCl_3$ (internal standard: 7.26 ppm, ^{1}H NMR; 77.36 ppm,^{13}C NMR) or [D_6]DMSO (internal standard: 2.54 ppm, ^{1}H NMR; 40.45 ppm, ^{13}C NMR) solutions at room temperature with Varian 400 spectrometer. Merck silica gel 60 (230–400 mesh) was used for the chromatography. The enantiomeric excess of the products was determined by HPLC using chiracel OD-H and OJ or chiralpak AD columns with hexane/isopropyl alcohol as eluent.

General Procedure A for the Allylation Reactions: The corresponding electrophile **3**–**4** (0.3 mmol) and $Pd_2(dba)_3$ (0.009 mmol) were dissolved in DMSO (3 mL) followed by addition of the allylic substrate **2a**–**g** (0.36 mmol). This reaction mixture was stirred for 10 min at room temperature under Ar. After addition of diboron reagent **1a** (0.36 mmol) the reaction mixture was stirred for the allotted temperatures and times listed in Table 1. Thereafter, the reaction mixture was diluted with water (3 mL) and stirred for one hour at room temperature. This solution was extracted with diethyl ether (4 × 6 mL), and the combined ether phases was dried with $MgSO_4$ and the solvents evaporated. The products **5**–**6** were isolated by column chromatography using a pentane/EtOAc eluent.

General Procedure B for the Allylation Reactions: The corresponding electrophile **3** (0.1 mmol) and $Pd_2(dba)_3$ (0.003 mmol) were dis-

solved in DMSO (0.7 mL). Thereafter, the allylic substrate **2a**–**f** (0.12 mmol) was added. This reaction mixture was stirred for 10 min at room temperature under Ar. After addition of diboron reagent **1b** (0.12 mmol) the reaction mixture was stirred until a clear yellow solution was obtained. Thereafter, toluene (0.7 mL) was added and the reaction mixture was stirred for the allotted temperatures and times listed in Table 1. Subsequently, the reaction mixture was diluted with water (1 mL) and stirred for one hour at room temperature, then the solution was extracted with diethyl ether (4×2 mL), and the combined ether phases was dried with $MgSO_4$ and the solvents evaporated. The products **5a**–**m** were isolated by column chromatography using a pentane/EtOAc eluent.

1-(4-Nitrophenyl)but-3-en-1-ol [5a, (*R*)-5a and (*S*)-5a]: General procedure A was employed for synthesis of the racemic product **5a**. The NMR spectroscopic data obtained of this product is in agreement with the literature values.[34,35] The enantiomerically enriched product (*R*)-**5a** was obtained using general procedure B. Optical rotation: $[\alpha]_D^{20}$ = +14.1 (*c* = 0.92, C_6H_6) for 53% *ee*; ref.[35] $[\alpha]_D^{20}$ = +21.5 (C_6H_6) for 81% *ee*. The same reaction (according to general procedure B) was performed with L-tartrate **1c** to afford the enantiomerically enriched product (*S*)-**5a**. Optical rotation: $[\alpha]_D^{20}$ = –28.0 (*c* = 0.67, $CHCl_3$) for 49% *ee*; ref.[36] $[\alpha]_D^{20}$ = –33.2 ($CHCl_3$) for 65% *ee*.

2-Methyl-1-(4-nitrophenyl)but-3-en-1-ol [(*R*)-5b and (*R*)-5b]: General procedure A was employed for synthesis of the racemic product. The NMR spectroscopic data obtained of this product is in agreement with the literature values.[37] General procedure B was employed to obtain the enantiomerically enriched product (*R*)-**5b**. Optical rotation: $[\alpha]_D^{20}$ = +23.0 (*c* = 0.54, $CHCl_3$) for 34% *ee*. The configuration was assigned on the basis of the optical rotation data reported for the parent compound (*R*)-**5i** (see below).

1-(4-Nitrophenyl)-2-phenylbut-3-en-1-ol (5c): General procedure A was employed for synthesis of the racemic product. The NMR spectrum is in agreement with the literature data.[18]

Ethyl 2-[Hydroxy(4-nitrophenyl)methyl]but-3-enoate (5d): General procedure A was employed for synthesis of this product. The NMR spectrum is identical with that reported in the literature.[18]

2-[Hydroxy(4-nitrophenyl)methyl]but-3-enamide (5e): General procedure A was employed for synthesis of the racemic product. The NMR spectrum is identical with that reported in the literature.[18]

1-[Hydroxy(4-nitrophenyl)methyl]allyl Acetate [5f[8] and (*S*)-5f]: General procedure A was employed for synthesis of the racemic product. The crude product was purified by silica gel chromatography using pentane/ethyl acetate (4:1) as eluent. ^{1}H NMR ($CDCl_3$): δ = 8.22 (d, *J* = 8.8 Hz, 2 H), 7.56 (d, *J* = 8.8 Hz, 2 H), 5.76 (ddd, *J* = 6.6 Hz, 10.4 Hz, 17.2 Hz, 1 H), 5.45 (dd, *J* = 6.6 Hz, 3.9 Hz, 1 H), 5.31 (d, *J* = 10.4 Hz, 1 H, *cis*), 5.26 (d, *J* = 17.2 Hz, 1 H, *trans*), 5.01 (t, *J* = 3.9 Hz, 1 H), 2.54 (d, *J* = 3.7 Hz, 1 H, *OH*) 2.09 (s, 3 H) ppm. ^{13}C NMR ($CDCl_3$): δ = 170.3, 146.8, 131.1, 128.8, 127.8, 123.8, 121.0, 78.3, 74.6, 21.4 ppm. General procedure B was employed to obtain the enantiomerically enriched product (*S*)-**5f**. Optical rotation: $[\alpha]_D^{20}$ = +27.8 (*c* = 0.39, $CHCl_3$) for 50% *ee*. The configuration was assigned on the basis of the optical rotation data reported for the hydrolysis product of the parent compound (*S*)-**5k** (see below).

2-[Hydroxy(4-nitrophenyl)methyl]but-3-enyl Acetate (5g):[8] General procedure A was employed for preparation of the racemic product. The crude product was purified by silica gel chromatography using pentane/diethyl ether (2:1) as eluent. ^{1}H NMR ($CDCl_3$): δ = 8.20 (d, *J* = 8.8 Hz, 2 H), 7.50 (d, *J* = 8.8 Hz, 2 H), 5.70 (ddd, *J* = 8.5 Hz, 10.4 Hz, 17.3 Hz, 1 H), 5.19 (d, *J* = 10.4 Hz, 1 H, *cis*), 5.04 (d, *J* = 17.3 Hz, 1 H, *trans*), 4.90 (d, *J* = 3.7 Hz, 1 H), 4.32 (dd, *J* = 11.2 Hz, 7.7 Hz, 1 H), 4.02 (dd, *J* = 11.2 Hz, 6.1 Hz, 1 H), 2.7 (m, 1 H), 2.66 (s, 1 H, *OH*), 2.08 (s, 3 H) ppm. ^{13}C NMR ($CDCl_3$): δ = 171.7, 149.8, 147.7, 132.8, 127.4, 123.8, 120.9, 72.2, 64.6, 51.1, 21.2 ppm.

1-Phenylbut-3-en-1-ol [(*R*)-5h]: This product was obtained by general procedure B. The NMR spectroscopic data are in agreement with the literature values.[35] Optical rotation: $[\alpha]_D^{20}$ = +24.0 (*c* = 0.67, benzene) for 45% *ee*; ref.[35] $[\alpha]_D^{20}$ = +51.2 (benzene) for 97% *ee*.

2-Methyl-1-phenylbut-3-en-1-ol [(*R*)-5i]: General procedure B was employed to obtain the enantiomerically enriched product (*R*)-**5i**. The NMR spectrum is identical with that reported in the literature.[38] Optical rotation: $[\alpha]_D^{20}$ = +57.0 (*c* = 0.46, $CHCl_3$) for 33% *ee*; ref.[39] $[\alpha]_D^{20}$ = +92.0 ($CHCl_3$) for 97% *ee*.

1,2-Diphenylbut-3-en-1-ol [(*R*)-5j]: General procedure B was employed to obtain this product. The NMR spectrum is identical with that reported in the literature.[40] Optical rotation: $[\alpha]_D^{20}$ = +5.5 (*c* = 0.74, $CHCl_3$) for 43% *ee*; ref.[40] given for the enantiomer form, (1*S*,2*R*)-1,2-diphenylbut-3-en-1-ol, $[\alpha]_D^{20}$ = –12.5 ($CHCl_3$) for 97.4% *ee*.

1-[Hydroxy(phenyl)methyl]allyl Acetate [(*S*)-5k]: This product was obtained by general procedure B. The NMR spectrum is identical with that reported in the literature.[41] Optical rotation: $[\alpha]_D^{20}$ = +19.7 (*c* = 0.23, $CHCl_3$) for 45% *ee*. Determination of the configuration is based on the optical rotation data published[42] for (1*S*,2*R*)-(+)-1-phenylbut-3-ene-1,2-diol which was obtained by hydrolysis of (*S*)-**5k**.

1-(Cyclohexyl)but-3-en-1-ol [(*R*)-5l]: This product was obtained by general procedure B. The NMR spectrum is identical with that reported in the literature.[43,44] Optical rotation: $[\alpha]_D^{20}$ = +3.0 (*c* = 0.68, EtOH) for 48% *ee*; ref.[44] $[\alpha]_D^{20}$ = +9.7 (EtOH) for 98% *ee*.

1-Cyclohexyl-2-phenylbut-3-en-1-ol [(*S*)-5m]: This product was obtained by general procedure B. The NMR spectrum is identical with that reported in the literature.[45] $[\alpha]_D^{20}$ = +42.2 (*c* = 0.36, $CHCl_3$) for 53% *ee*. The configuration was assigned on the basis of the optical rotation data reported for the phenyl analog (*R*)-**5j** (see above).

***N*-(1-Phenylbut-3-enyl)benzenesulfonamide (6a):** Both procedures (A and B) gave racemic products. The NMR spectrum is identical with that reported in the literature.[33]

***N*-(1,2-Diphenylbut-3-enyl)benzenesulfonamide (6b):** General procedure A was employed for synthesis of this product. The NMR spectrum is identical with that reported in the literature.[18]

Ethyl 2-[Phenylsulfonylamino(phenyl)methyl]but-3-enoate (6c): General procedure A was employed for synthesis of this product. The NMR spectrum is identical with that reported in the literature.[18]

2-[Phenylsulfonylamino(phenyl)methyl]but-3-enamide (6d):[8] This product was obtained by general procedure B. The crude product was purified by silica gel chromatography using dichloromethane/methanol (20:1) as eluent. ^{1}H NMR ([D$_6$]DMSO): δ = 8.28 (d, *J* = 9.4 Hz, 1 H, *NH*), 7.48 (d, *J* = 7.4 Hz, 2 H), 7.39 (t, *J* = 7.4 Hz, 1 H), 7.26 (t, *J* = 7.4 Hz, 2 H), 7.04 (m, 5 H), 5.69 (ddd, *J* = 10.2 Hz, 10.0 Hz, 17.1 Hz, 1 H, *anti*), 5.51 (ddd, *J* = 9.4 Hz, 10.2 Hz, 17.2 Hz, 1 H, *syn*), 5.22 (d, *J* = 17.1 Hz, 1 H, *trans*, *anti*), 5.08 (d, *J* = 10.0 Hz, 1 H, *cis*, *anti*), 4.84 (d, *J* = 17.2 Hz, 1 H, *trans*, *syn*), 4.80 (d, *J* = 10.2 Hz, 1 H, *cis*, *syn*), 4.68 (t, *J* = 9.4 Hz, 1 H, *syn*), 4.55 (t, *J* = 10.2 Hz, 1 H, *anti*), 3.28 (t, *J* = 10.2 Hz, 1 H, *anti*), 3.17 (t, *J* = 9.4 Hz, 1 H, *syn*) ppm. ^{13}C NMR ([D$_6$]DMSO): δ =

173.4, 142.4, 139.9, 135.7, 132.4, 129.2, 128.6, 128.2, 127.7, 127.2, 118.8, 60.1, 58.1 ppm.

Supporting Information (see also footnote on the first page of this article): It contains the ^{13}C NMR spectra of synthetized compounds **5a**–**m** and **6a**–**d**.

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