CHEMISTRY
A EUROPEAN JOURNAL

DOI: 10.1002/chem.200600406

Regio- and Stereoselective Palladium-Pincer Complex Catalyzed Allylation of Sulfonylimines with Trifluoro(allyl)borates and Allylstannanes: A Combined Experimental and Theoretical Study

Olov A. Wallner and Kálmán J. Szabó*[a]

Abstract: Regio- and stereoselective palladium-pincer complex catalyzed allylation of sulfonylimines has been performed by using substituted trifluoro(allyl)borates and trimethylallylstannanes. The reactions provide the corresponding branched allylic products with excellent regioselectivity. The stereoselectivity of these processes is very high when trifluoro(cinnamyl)borate and trimethyl cinnamyl stannane are employed as allylic precursors; however, the reaction with trifluoro(crotyl)borate results in poor stereoselectivity. The major diastereomer formed in these reactions was the *syn* isomer, while the (previously reported) reactions with aldehyde electrophiles afforded the *anti* products, indicating that the mechanism of the stereoselection is dependent on the applied electrophile. Therefore, we have studied the mechanistic aspects of the allylation reactions by experimental studies and DFT modeling. The experimental mechanistic studies have clearly shown that potassium trifluoro(allyl)borate undergoes transmetallation with palladium-pincer complex **1a** affording an η^1-allylpalladium-pincer complex (**1e**). The mechanism of the transfer of the allyl moiety from palladium to the sulfonylimine substrate was studied by DFT calculations at the B3PW91/LANL2DZ+P level of theory. These calculations have shown that the electrophilic substitution of sulfonylimines proceeds in a one-step process with a relatively low activation energy. The topology of the potential energy surface in the vicinity of the transition-state structure proved to be rather complicated as nine different geometries with similar energies were located as first order saddle points. Our studies have also shown that the high stereoselectivity with cinnamyl metal reagents stems from steric interactions in the TS structure of the allylation reaction. In addition, these studies have revealed that the mechanism of the stereoselection in the allylation of aldehydes and sulfonylimines is fundamentally different.

Keywords: allylation · density functional calculations · diastereoselectivity · electrophilic addition · palladium

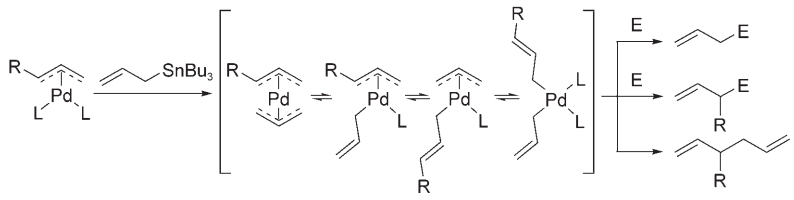
Introduction

Palladium-catalyzed nucleophilic allylic substitution is an important and versatile synthetic procedure for generating new carbon–carbon and carbon–heteroatom bonds.[1,2] Although application of nucleophiles in allylic substitution reactions is a well established area in palladium catalysis, employment of electrophilic reagents still receives a lot of current interest.[3–18] It has been shown that palladium catalysts can be employed for the electrophilic allylation of variety of electrophiles, such as aldehydes and imines. Most of these allylation reactions are based on catalytic formation of a bis(allyl)palladium intermediate, which subsequently reacts with the electrophile (Scheme 1).[3–12] However, the diverse reactivity of bis(allyl)palladium intermediates imposes several synthetic limitations on these processes. For example, the control of the chemo- and regioselectivity of the catalytic transformations may be difficult because of the isomerization processes of the bis(allyl)palladium intermediates (Scheme 1).[7–9,19–21]

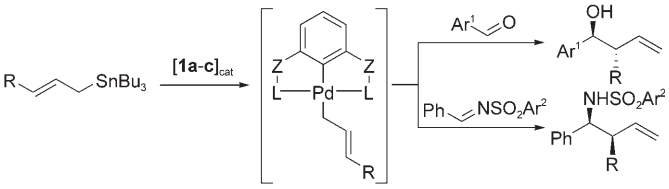
Recently, however, we have reported[14–18] a new catalytic application proceeding through a (mono)allylpalladium intermediate, which undergoes regioselective electrophilic allylation of aldehydes and sulfonylimines (Scheme 2). In these processes so-called palladium-pincer complexes[22–28] (comprising terdentate ligands) were applied as catalysts. It was shown that most of the limitations of the electrophilic allylation reactions via bis(allyl)palladium intermediates

[a] Dr. O. A. Wallner, Prof. Dr. K. J. Szabó
Stockholm University, Arrhenius Laboratory
Department of Organic Chemistry
106 91 Stockholm (Sweden)
Fax: (+46) 8-154-908
E-mail: kalman@organ.su.se

Supporting information for this article is available on the WWW under http://www.chemeurj.org/ or from the author.

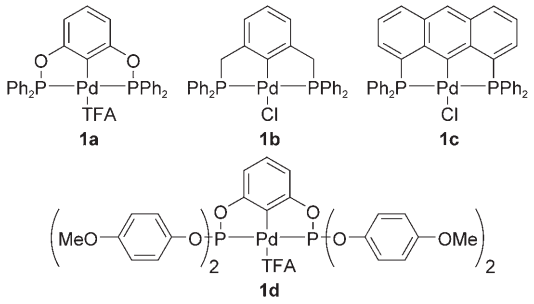


Scheme 1. Electrophilic allylation via a bis(allyl)palladium intermediate.



Scheme 2. Palladium-pincer complex catalyzed electrophilic allylation.

(Scheme 1) can be avoided by using these catalysts. A wide variety of palladium-pincer complexes[29–32] can be employed in these transformations; however, phosphorous-based complexes **1a**–**c** produced the highest catalytic activity in the allylation reaction. The pincer complex catalyzed transformations proceed with excellent regioselectivity, providing the branched allylic isomer, while the stereochemistry of the allylation is dependent on the applied electrophile.[14–17] Thus, the reaction proceeds with *anti* selectivity for allylation of aldehydes, while predominantly the *syn* diastereomer is formed when using sulfonylimines as substrates (Scheme 2)

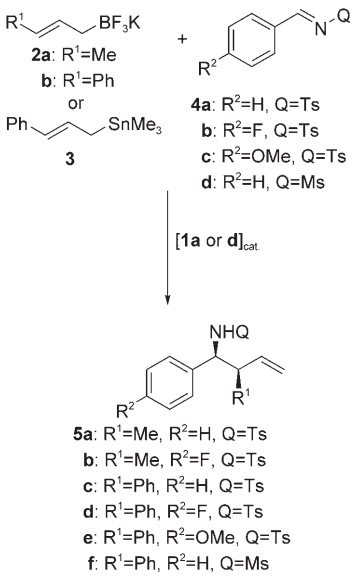


DFT modeling of the allylation of aldehyde electrophiles revealed[15] that the role of the terdentate pincer ligand is to render the allyl moiety nucleophilic by formation of an η^1-allylpalladium intermediate.[15] These studies also showed that the reaction takes place at a single coordination site on palladium, and the coupling to the aldehyde proceeds at the γ-carbon of the allyl moiety. Allylation of imines[5,33–38] is usually a more challenging task than that of aldehydes, and therefore it is desirable to develop new regio- and stereoselective synthetic solutions for this reaction. However, the mechanism of the palladium-pincer complex catalyzed reaction of allylic substrates with imines has not been investigated before, and thus the *syn* diastereoselectivity of the reaction is not fully understood. Thus, we decided to explore the synthetic scope of these processes by employment of substituted allylstannanes and potassium trifluoro(allyl)borates, as well as to study the mechanism of the pincer complex catalyzed electrophilic allylation of sulfonylimines. These studies involve employment of various allylic substrates (**2**–**3**) with different steric bulk and imines (**4a**–**d**) comprising both electron-withdrawing and -donating substituents. We have also studied the formation of the active catalytic intermediate from potassium trifluoro(allyl)borate and palladium-pincer complex **1a**. Furthermore, we carried out DFT-modeling studies to explore the mechanism of the allylation process of sulfonylimines and to understand the *syn* selectivity of the reaction. We have also analyzed the mechanistic differences between the palladium-pincer complex catalyzed allylation of imines and aldehydes.[14–17]

Experimental Studies

We have recently shown that palladium-pincer complexes are highly active catalysts in the coupling reaction of allylstannanes with aldehydes and sulfonylimines.[14–16] The employed mild reaction conditions allowed for the presence of many functional groups. This reaction is highly regioselective, as the branched homoallylic product is formed upon employment of substituted allylic substrates. Interestingly, the reaction of substituted allylstannanes with aldehydes proceeds with *anti* selectivity, while the corresponding reaction with imines affords the *syn* products. Subsequently, we have demonstrated that potassium trifluoro(allyl)borate can be used as allylating reagent in place of allylstannanes.[17] Application of this reagent represents an important step for broadening the synthetic scope of electrophilic allylation reactions, as functionalized trifluoro(allyl)borates are more easily accessible[39,40] and more stable reagents than allylstannanes. Another advantage is that substituted trifluoro(allyl)borates are less sensitive to *cis*–*trans* isomerization than the corresponding allylstannanes. For example, crotyl trifluoro(allyl)borates can be produced and stored as pure *Z*[39] and *E* isomers,[39,40] whereas the crotyl stannanes readily undergo isomerization affording a mixture of *E*/*Z* isomers. Recently, we have reported[40] a new simple method for the synthesis of functionalized trifluoro(allyl)borates, which allows the study of the reactivity and selectivity of substituted allyl boronates, such as cinnamyl derivative **2b**.

To investigate the stereoselectivity of the palladium-pincer complex catalyzed allylation of sulfonylimines we employed methyl and phenyl-substituted trifluoro(allyl)borates (**2**) and allylstannane (**3**) reagents (Scheme 3 and Table 1). The sulfonylimine reagents (**4a**–**d**) comprised electron-withdrawing and -donating groups so that the substituent effects of the electrophile on the stereoselectivity of



Scheme 3. Stereoselective palladium-pincer complex catalyzed allylation of sulfonylimines.

Table 1. Diastereoselective palladium-pincer complex catalyzed allylation of sulfonylimines

Entry	Allyl	Imine	Cat.	Conditions [°C]/[h][a]	Solvent	Product	Yield [%][b]	*dr*[c]
1	**2a**	**4a**	**1d**	25/48	DMF	**5a**	60	6:5
2	**2a**	**4b**	**1d**	25/48	DMF	**5b**	80	6:5
3	**2b**	**4a**	**1a**	20/17	DMF	**5c**	77	9:1
4	**3**	**4a**	**1a**	40/20	THF	**5c**	80	10:1
5	**3**	**4a**	**1d**	25/20	THF	**5c**	77	10:1
6	**3**	**4b**	**1a**	40/24	THF	**5d**	75	10:1
7	**3**	**4c**	**1a**	40/36	THF	**5e**	77	19:1
8	**3**	**4d**	**1a**	20/24	THF	**5f**	80	19:1

[a] Reaction temperature/time. [b] Isolated yield. [c] Diastereomeric ratio (*syn*/*anti*) determined by ^{1}H NMR spectroscopy.

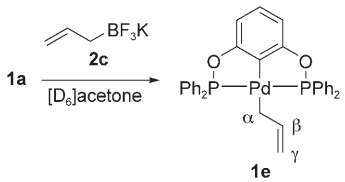
the process could be studied. The reactions of allyl boronates **2a**–**b** with sulfonylimines **4a**–**b** were conducted in the presence of 5 mol% of the catalyst **1a** or **1d**[41] (Scheme 3). In these reactions, DMF was employed as the solvent as both the catalysts and potassium trifluoro(allyl)borate salts were readily soluble in this solvent. Previously, we have shown[17] that pincer complex **1a**[29] catalyses the reaction of crotyl borate **2a**[39] with imine **4a** at 40°C (in 48 h) affording the branched allylic product **5a**. However, by using this catalyst (**1a**), the isolated yield was only 40% and the *syn*/*anti* selectivity was low (65:35). We envisioned that the bisphosphite-based pincer complex **1d**[41] would provide a higher reactivity than **1a**, because of the high π-acceptor ability[42,43] of the pincer ligand. Indeed, by using **1d** as the catalyst (entry 1) the reaction can be conducted at 25°C with increased yield (60%); however, the stereoselectivity of the reaction was poor (6:5). Employment of fluoro-substituted imine **4b** (entry 2) resulted in an even higher yield (80%) of the corresponding product (**5b**), although with the same low diastereomeric ratio (6:5). Potassium cinnamyl borate (**2b**)[40] reacted readily with **4a** in the presence of **1a** (entry 3) affording homoallylic amine **5c** in 77% yield and with 9:1 *syn*/*anti* selectivity. The high diastereoselectivity in this reaction indicates the importance of the steric effects of the allylic substituents on the stereoselectivity of the process (compare entries 1 and 3).

We also compared the reactivity of allyl boronates and allylstannanes. Interestingly, cinnamyl stannane **3** reacted somewhat slower than its boronate analogue **2b** (compare entries 3 and 4). Similar to allyl boronate **2a** (entries 1 and 2), allylstannane **3** also reacted faster with catalyst **1d** than with **1a** (entries 5 and 6), without altering the diastereoselectivity of the process. The reaction rates also depend on the substituent effects of the applied imines. The parent imine **4a** and the fluoro-substituted derivative **4b** react faster than the methoxy derivative **4c** (entries 5–7). The regio- and stereoselectivity of the allylation is very similar for allyl boronates and allylstannanes (compare entries 3 and 4). The presence of an electron-withdrawing fluorine in the imine component did not affect the stereoselectivity of the reaction (compare entries 5 and 6). On the other hand, application of a methoxy substituent in imine **4c** (entry 7) improved the diastereoselectivity of the process (19:1).

We also investigated the importance of the steric bulk of the sulfonyl group on the reactivity and selectivity of the reaction. It was found that methane-sulfonylimine **4d** is more reactive than **4a** and that the diastereoselectivity for formation of **5f** (19:1) is somewhat higher than for **5c** (10:1). This higher selectivity can probably be ascribed to the fact that a lower reaction temperature was required to synthesize **5f**.

Stoichiometric Reaction with Trifluoro(allyl)borate

We have previously shown[15] that the active allylating agent in the coupling reaction of allylstannanes with aldehydes or sulfonylimines is an η^1-(mono)allylpalladium complex formed from complex **1a**. As shown above, allyl boronates are promising alternative reagents for the allylation of imines, and therefore we wanted to ensure that the active allylating agent of the reaction is the same as with allylstannanes. Thus, we studied the stoichiometric reaction of trifluoro(allyl)borate (**2c**) with **1a** in [D$_6$]acetone (Scheme 4). The ^{1}H NMR spectrum of the process (Figure 1) clearly shows the characteristic signals[15] of the α- and γ-protons of the η^1-allyl moiety of **1e** appearing at $\delta =$ 2.30, 3.85, and 4.16 ppm, respectively (Figure 1).



Scheme 4. Reaction studied by NMR spectroscopy.

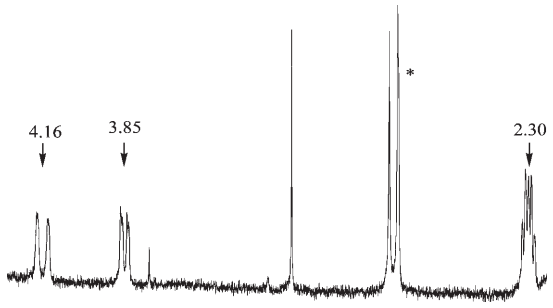


Figure 1. Truncated ^{1}H NMR spectrum of **1e**; * = H_2O/HDO.

The ^{31}P NMR spectrum of this reaction shows a sole singlet at 148.5 ppm, indicating that both phosphorous atoms are symmetrically coordinated to palladium in **1e** (Scheme 4). Considering the above we conclude that by using either allyl boronate or allylstannane reagents, complex **1e** is the active intermediate in pincer complex catalyzed allylation of imines with **1a**.

There is, however, an interesting difference in formation of **1e** from allyl boronates or from allylstannanes. The reaction of allyl boronate **2c** and **1a** was completed in about 15 min at 25 °C, involving a full conversion of **1a** to **1e** (Scheme 4). On the other hand, the analogue reaction using allylstannanes with **1a** is an equilibrium process,[15] and therefore **1a** could be observed in the reaction mixture, even in the presence of large excess of allylstannane.

DFT Modeling of the Electrophilic Allylation of Sulfonylimines

The above experimental studies clearly indicate that the active intermediate of the allylation reaction is complex **1e**, formed from the allylating reagent (**2** or **3**) and **1a**. A further important step of the catalytic reaction is the transfer of the allylic moiety from **1e** to the imine substrate (**4**). As shown above, by using substituted allylating reagents this reaction proceeds with *syn* stereoselectivity. This selectivity is in sharp contrast with the selectivity in the allylation of aldehydes occurring with predominant formation of the *anti* diastereomer.[15] The different stereoselectivity indicates important mechanistic differences in allylation of imines and aldehydes. To gain insight into the mechanism of the transfer of the allyl moiety from palladium to sulfonylimines, we carried out DFT calculations. The results of these calculations were also compared to the DFT-modelling studies on the allylation of aldehydes to analyze the mechanistic differences between substitution of aldehyde and imine substrates.

Computational methods: All geometries were fully optimized employing a Becke-type[44] three-parameter density functional model B3PW91 with a double-ζ(DZ)+P basis constructed from the LANL2DZ basis[45–47] by adding one set of polarization functions to the heavy atoms (exponents: C 0.630, N 0.864, O 1.154, P 0.340, S 0.410) and one set of diffuse d-functions on palladium (exponent: 0.0628). Harmonic frequencies have been calculated at the level of optimization for all structures to characterize the calculated stationary points and to determine the zero-point energies. Fully optimized transition-state structures **7a–i** and **9a–b** (Figure 2) have been characterized by a single imaginary

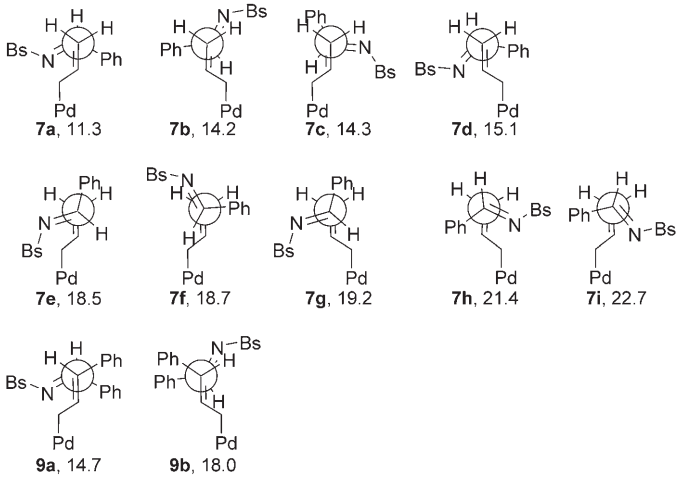
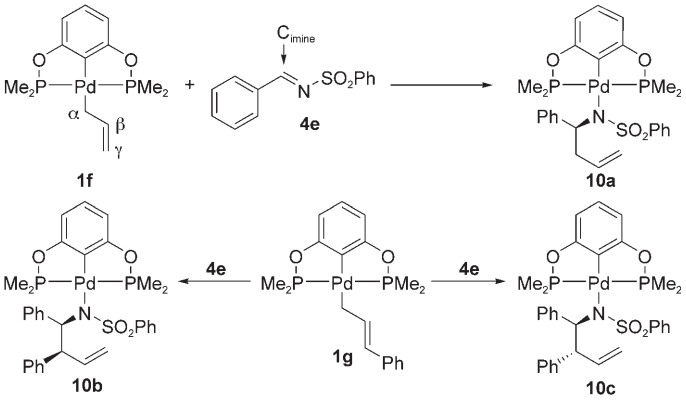


Figure 2. Simplified Newman projections of the optimized transition states (the pincer ligand is omitted for clarity), Bs = SO_2Ph. The activation energies are given in kcal mol^{-1}.

frequency, while the rest of the optimized structures possess only real frequencies. All calculations were carried out by employing the Gaussian 03 program package.[48]

Reaction profile for the electrophilic allylation reaction: The DFT calculations involved exploration of the possible reaction paths for transferring the η^1-allyl moiety from palladium to the imine substrate. The most important part of these studies is focused on exploration of the potential energy surface (PES) in the vicinity of the transition-state (TS) structure of the reaction. Subsequently, we have also studied the factors influencing the diastereoselectivity of the reaction. Because of computational limitations, we employed slightly simplified model systems of the experimentally studied reactions of imine **4** with allylating reagents **2** or **3**. Thus, we have approximated (Scheme 5) the phenyl groups in palladium-pincer complex **1a** with methyl groups (**1f**), and the tolyl group of **4a** was approximated with a phenyl group (**4e**).

It was found (Figures 2, 3, 4, 5 and Scheme 5) that the initial step of the allyl-transfer reaction is formation of an electrostatic complex (**6**) from η^1-palladium complex **1f** and imine **4e**. In this electrostatic complex (Figure 4), the closest contact between **1f** and **4e** is 2.49 Å between the sulfonyl group of **4e** and one of the methyl groups in the side arms of **1f**. Both phosphorous atoms in **6** are firmly coordinated to palladium (P–Pd 2.30 Å) and the allyl moiety is coordinated in an η^1-fashion (C_α–Pd 2.158 Å).



Scheme 5. Reactions studied by DFT calculations.

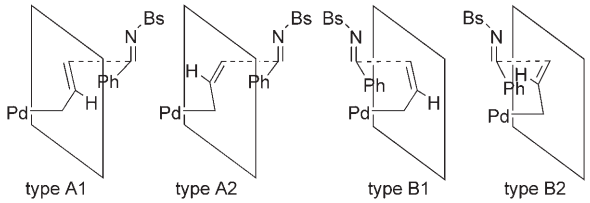


Figure 3. The four different types of transition states investigated (the pincer ligand is omitted for clarity). The plane of the allyl is defined by C_α, C_β, and C_γ.

The potential energy surface for the formation of the C_γ–C_{imine} bond is rather complicated and we were able to locate a total of nine discrete TS structures (**7a–i**, Figures 3 and 4). The Newman projections along the forming new C_γ–C_{imine} bonds of the TS structures are given in Figure 2. The TSs can be classified according to the relative position of the palladium atom and the imine substrate with respect to the C-C-C plane of the allyl moiety. Thus, in type A TSs (**7a–d**) the palladium atom and the imine substrate **4e** are located on the opposite sides of the C-C-C plane of the allyl moiety, while in type B TSs (**7e–i**) the palladium atom and **4e** are residing on the same side of this plane (Figure 3). There are also two subclasses of the TS structures, depending on the position of the central C–H bond of the allyl moiety. In types A1 and B1 this C–H bond points to the right-hand side, while in types A2 and B2 the C–H bond points to the left-hand side.

We have obtained two different TS structures each for type A1 (**7a** and **7c**), type A2 (**7b** and **7d**), and type B2 (**7g** and **7h**), while for type B1 three TS structures (**7e**, **7f**, and **7i**) were found. The activation energies obtained for type A TSs (11.3–15.1 kcal mol^{-1}) are invariably lower than for type B TSs (18.5–22.7 kcal mol^{-1}). This can be ascribed to the repulsive steric interactions between imine **4e** and the pincer ligand in the type B TS structures. The developing C_γ–C_{imine} bonds represent the major component of the transition vectors of the reaction. Their lengths vary in a narrow range of 2.00–2.12 Å. Notably, the palladium–nitrogen distances are very long (3.9–5.9 Å), even in type B TSs, in which coordination of the imine nitrogen to the palladium atom is allowed by the geometry. This indicates that the nitrogen atom of **4e** does not interact with the central metal atom in the TS of the reaction. On the contrary, in the TS structure for allylation of the aldehyde substrate (Figure 5) the oxygen atom of the aldehyde is clearly coordinated to palladium.[15]

The lowest energy path for the allylation reaction of **4e** with **1f** (**6**→**7a**→**10a**, Figure 6) proceeds by TS **7a**, requiring a relatively low activation energy of 11.3 kcal mol^{-1}. The overall reaction is strongly exothermic by 26.5 kcal mol^{-1} resulting in homoallylic amide coordinated palladium-pincer complex **10a** (Scheme 5).

The geometry of the TS structures: The calculated structure of **7a** reveals that the topology of the pincer complex is preserved (P–Pd 2.31 Å and C_{aryl}–Pd 2.035 Å) in the TS indicating that the allyl-transfer process requires a single coordination site on palladium. Comparing the structure of complex **6** and TS structure **7a** reveals some systematic changes of the bond lengths on formation of the new C_γ–C_{imine} bond (2.102 Å). The Pd–C_α bond is elongated from 2.158 (**6**) to 2.220 Å (**7a**), the C_α–C_β bond is shortened from 1.474 to 1.418 Å, and the former double bond between C_β and C_γ is also elongated from 1.357 to 1.403 Å. These geometrical changes indicate that formation of the new C_γ–C_{imine} bond, cleavage of the Pd–C bond, and isomerization of the C–C double bond takes place simultaneously. As pointed out above, in **7a** the imine nitrogen does not coordinate to palladium (Pd–N 5.167 Å), despite of the fact that a negative charge evolves on the nitrogen atom in the TS. A possible explanation is that the sulfonyl moiety of the imine efficiently delocalizes the negative charge on the nitrogen atom, and therefore the driving force for a stabilizing palladium-nitrogen interaction is missing.

The alternative reactions by type A1 and A2 (**7b–7d**, Figures 2 and 4) TSs require 2.9–3.8 kcal mol^{-1} higher activation energy than the process proceeding through **7a**. The higher activation energies are due to an increased steric repulsion between the sulfonyl group of the imine and the pincer ligand. The transition states **7e–7i** (Figures 2 and 4), which are of type B1 and B2, are more sterically congested than transition states of type A1 and A2, which is reflected by the increased activation energies (18.5–22.7 kcal mol^{-1}) for these reaction pathways. Although the imine nitrogen and palladium are located on the same side of the C-C-C plane of the allyl moiety, there is no coordinative interaction between palladium and nitrogen (Pd–N 3.95–5.14 Å), which is again due to the efficient delocalization of the negative charge on nitrogen into the sulfonyl group. The large distances between the oxygen atoms of the sulfonyl group and palladium (Pd–O = 3.25–6.09 Å) indicate that the palladium-oxygen coordination is missing.

Study on the stereoselectivity of the allylation reaction: As was shown in the experimental studies, cinnamyl derivatives **2b** and **3** react with high *syn* diastereoselectivity with tosyl-

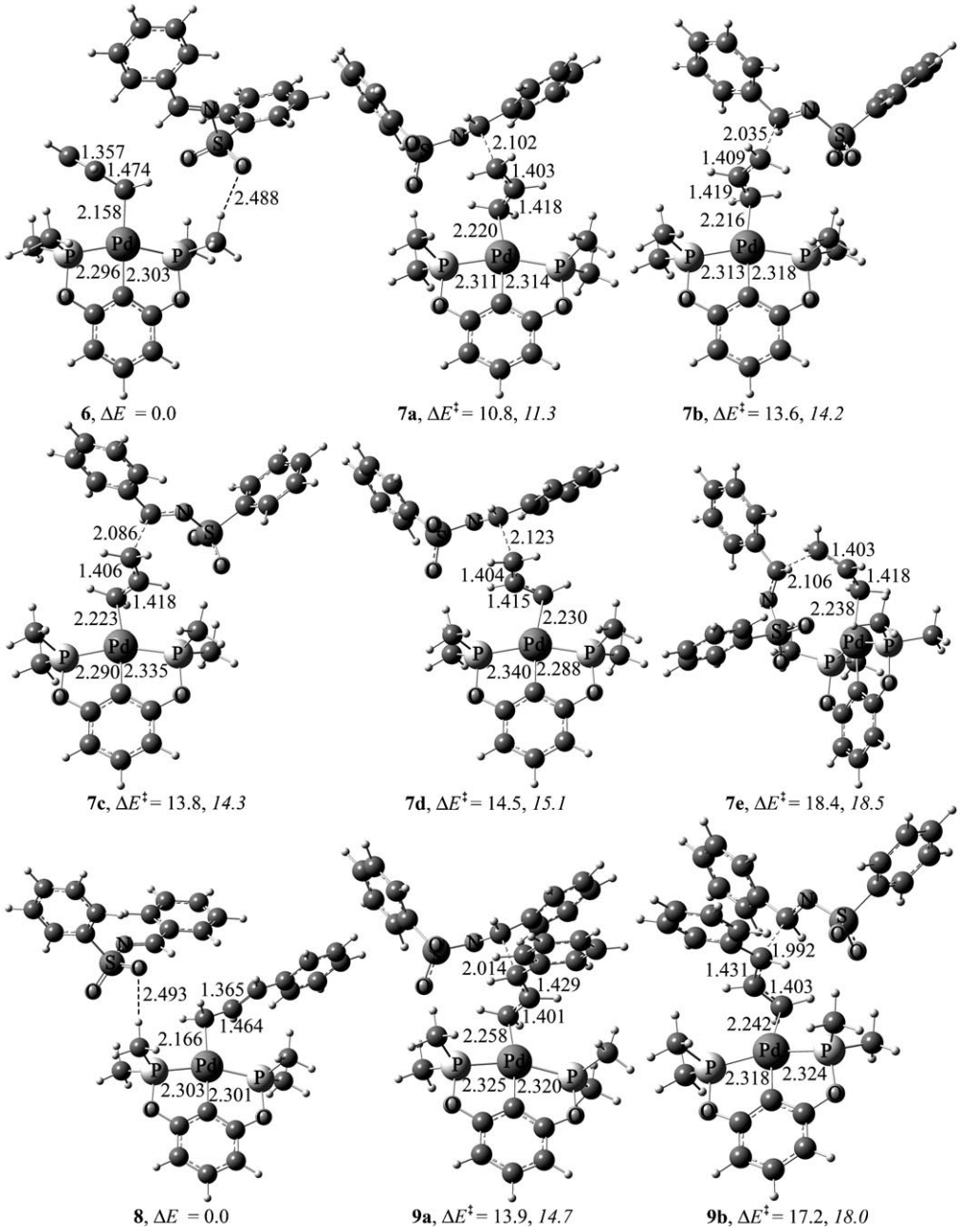


Figure 4. Selected geometries and transition states of the allylation reactions optimized at the B3PW91/LANL2DZ+P level of theory. Bond lengths are given in Å, energies in kcal mol^{-1}, and the ZPV corrected energies in italics.

imine **4a** (and other imines). Therefore, by using the above results obtained for the allyl-transfer process we have studied the development of the stereoselectivity for transfer of the phenyl-substituted analogue from **1g** to imine **4e** affording either the *syn* isomer **10b** or *anti* isomer **10c** (Scheme 5). These studies have shown that the transfer of the cinnamyl group is initiated by formation of electrostatic complex **8**, which is the phenyl-substituted analogue of **6**. Similarly to **6**, in **8** the cinnamyl palladium complex **1g** and imine **4e** are separated by 2.49 Å. Formation of the *syn* product **10b** proceeds by TS structure **9a**, requiring 14.7 kcal mol^{-1} in activation energy. Except for the phenyl substituent, the TS structure **9a** is very similar to **7a** (see also the Newman projections in Figure 2), which is the lowest energy TS structure for the allyl-transfer process. Surprisingly, the activation energy of the cinnamyl substitution is only 3.4 kcal mol^{-1} higher than for the allylation reaction (Figure 6). Formation of the *anti* isomer **10c** proceeds through TS structure **9b**, which can be derived from **7b** by phenyl substitution. The activation barrier for formation of the *anti* isomer **10c** is 18.0 kcal mol^{-1}, which is 3.3 kcal mol^{-1} higher than the activation energy for formation of the *syn* isomer **10b**. These re-

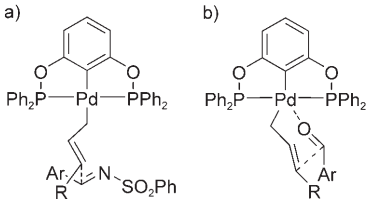


Figure 5. Transition state for palladium-pincer complex catalyzed allylation of sulfonylimine (a) and aldehyde (b) electrophiles.

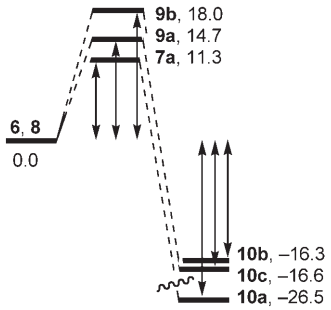


Figure 6. PES of the palladium-pincer complex catalyzed allylation reaction.

sults, indicating that the formation of the *syn* diastereomer requires lower activation energy than formation of the *anti* diastereomer, are in agreement with our experimental results, which show a predominant formation of the *syn* isomer in the allylation of sulfonylimines **4a–d** with allylstannanes and allyl boronates (Table 1 entries 3–8). The difference in the activation energy for formation of the *syn* and *anti* products can be explained by the repulsive interaction between the imine substituent and the pincer complex in the corresponding TS. These repulsive interactions are more extensive in **9b** (giving the *anti* product) than in **9a** (giving the *syn* product). Considering the complexity of the PES for the allyl-transfer process involving nine TS structures (**7a–i**), there are certainly further TS structures in the PES of the cinnamyl-transfer process. These TS structures can be derived from **7c–i** by phenyl substitution. However, as the activation energies of **7c–i** are higher than those of **7a–b** (and most of them are higher than that of **9a**), we did not attempt to localize these TS structures.

Formation of the *syn* (**8**→**9a**→**10b**) and the *anti* (**8**→**9b**→**10c**) isomers is exothermic by 16.3 and 16.6 kcal mol^{-1}, respectively. As the *anti* product is slightly more stable (by 0.3 kcal mol^{-1} than the *syn* product, the high *syn* selectivity of the cinnamyl-transfer process is obviously determined by the activation energies, that is, the higher stability of TS **9a** compared to TS **9b**.

Comparison of the transition-state structures for allylation of imine and aldehyde electrophiles: As pointed out above, the stereoselectivity of the pincer complex catalyzed allylation of aldehydes and imines is different. The most important differences are found for allylic substrates with phenyl or aryl substituents (such as **2b** and **3**). For example, trimethyl cinnamyl stannane gives predominantly the *anti* diastereomer with benzaldehyde[15] while the *syn* diastereomer is formed in the reaction with sulfonylimine **4a** (Table 1, entries 4 and 5). The different stereoselectivity clearly indicates the important mechanistic differences between these allylation processes. Considering the above and our previous DFT-modeling results[15] the mechanistic differences can easily be pointed out. In the TS structure of the allylation of aldehyde (Figure 5) the negatively charged oxygen atom of the aldehyde unit coordinates to palladium. This coordination leads to formation of a six-membered-ring TS with a well-defined chair conformation. In case of allylation of the imine substrate, the nitrogen atom of the sulfonylimine unit does not coordinate to palladium as the negative charge is efficiently delocalized to the sulfonyl group. Therefore, the sulfonylimine substrate does not form a six-membered ring TS with the allyl moiety and palladium. This has two important consequences: (1) The imine substrate and palladium are not necessarily located at the same side of the C-C-C plane of the allyl moiety, as for allylation of aldehydes. In fact, the TS structures in which the imine and palladium are located on the opposite sides of the C-C-C plane of the allyl moiety (type A TSs, Figure 3) have a lower energy than the TS structures in which the substrate and the pincer ligand are close to each other (type B TSs). (2) As the substrate and the allyl moiety does not form a well-defined six-membered-ring TS, the number of the possible TS structures is higher for the allylation of imines than for the allylation of aldehydes. For the allylation of imines, the main factor determining the stereoselectivity of the process is the steric interactions between the oxygen atoms of the sulfonyl group and the pincer ligand leading to *syn* diastereoselectivity. On the other hand, for the allylation of aldehydes the stereoselectivity is determined by the steric interaction between the aryl substituent of the aldehyde and the substituent (R) of the allyl moiety in the six-membered TS structure favoring *anti* diastereoselectivity.

Concluding Remarks

Highly regio- and stereoselective pincer complex catalyzed allylation of sulfonylimines was achieved by employment of trifluoro(cinnamyl)borate and trimethyl cinnamyl stannane. The reaction provides the branched homoallylic products with high (up to 19:1) *syn* selectivity. On the other hand, the stereoselectivity is poor when the corresponding crotyl derivatives are used as the allyl precursor. Bisphosphite pincer complex **1d** displays somewhat higher catalytic activity than complex **1a**; however, the diastereoselectivity of the catalytic reaction with **1a** and **1d** is about the same. Stoichiometric reactions of trifluoro(allyl)borate and pincer complex **1a** showed that the reactive allylating agent is an η^1-allylpalladium intermediate (**1e**). DFT-modeling studies show that the transfer of the allyl moiety from palladium to the imine proceeds through an acyclic TS, in which the negatively charged nitrogen atom of the imine component does not co-

ordinate to palladium. In the TS structure of the allylation reaction, the steric interactions between the imine substrate and the pincer complex disfavor the formation of the *anti* diastereomer, and therefore predominantly the *syn* product is formed.

Experimental Section

The experimental and computational details of this study in addition to characterization of the products **5a–f** are given in the Supporting Information. This section gives only the general procedures of the pincer complex catalyzed allylation reactions.

General procedure A

Palladium-pincer complex catalyzed allylation of sulfonylimines with potassium trifluoro(allyl)borates: The corresponding sulfonylimine (0.20 mmol), catalyst **1a** or **1d** (0.010 mmol), potassium trifluoroborate **2a** or **2b** (0.24 mmol), and 4 Å molecular sieves (50 mg) were dissolved in DMF (0.50 mL). Subsequently, the reaction mixture was stirred for the allotted time and at the temperature given in Table 1; thereafter, the reaction mixture was poured into H_2O (2 mL) and extracted with EtOAc (5×2 mL). After evaporation of the solvent, the crude product was purified by silica-gel chromatography.

General Procedure B

Palladium-pincer complex catalyzed allylation of sulfonylimines with trimethyl cinnamyl stannane: The corresponding sulfonylimine (0.20 mmol), catalyst **1a** or **1d** (0.010 mmol), and 4 Å molecular sieves (50 mg) were dissolved in THF (0.50 mL) followed by addition of trimethyl cinnamyl stannane **3** (68 mg, 0.24 mmol). Thereafter, the reaction mixture was stirred for the allotted time and at the temperature given in Table 1. After evaporation of the solvent, the crude product was purified by silica-gel chromatography.

Acknowledgements

This work was supported by the Swedish Natural Science Research Council (VR). The calculations were conducted at the parallel computer facility of the Parallelldatorcentrum (PDC) at the Royal Institute of Technology (Sweden). The authors thank the PDC for a generous allotment of computer time.

[1] J. Tsuji, *Palladium Reagents and Catalysis. New Perspectives for the 21st Century*, Wiley, Chichester, **2004**.
[2] J. Tsuji, *Palladium Reagents and Catalysis: Innovations in Organic Synthesis*, Wiley, Chichester, **1995**.
[3] H. Nakamura, H. Iwama, Y. Yamamoto, *J. Am. Chem. Soc.* **1996**, *118*, 6641.
[4] H. Nakamura, J.-G. Shim, Y. Yamamoto, *J. Am. Chem. Soc.* **1997**, *119*, 8113.
[5] H. Nakamura, K. Nakamura, Y. Yamamoto, *J. Am. Chem. Soc.* **1998**, *120*, 4242.
[6] H. Nakamura, K. Aoyagi, J.-G. Shim, Y. Yamamoto, *J. Am. Chem. Soc.* **2001**, *123*, 372.
[7] H. Nakamura, M. Bao, Y. Yamamoto, *Angew. Chem.* **2001**, *113*, 3308; *Angew. Chem. Int. Ed.* **2001**, *40*, 3208.
[8] N. Solin, S. Narayan, K. J. Szabó, *J. Org. Chem.* **2001**, *66*, 1686.
[9] N. Solin, S. Narayan, K. J. Szabó, *Org. Lett.* **2001**, *3*, 909.
[10] O. A. Wallner, K. J. Szabó, *Org. Lett.* **2002**, *4*, 1563.
[11] O. A. Wallner, K. J. Szabó, *Chem. Eur. J.* **2003**, *9*, 4025.
[12] O. A. Wallner, K. J. Szabó, *J. Org. Chem.* **2003**, *68*, 2934.
[13] K. J. Szabó, *Chem. Eur. J.* **2004**, *10*, 5268.
[14] N. Solin, J. Kjellgren, K. J. Szabó, *Angew. Chem.* **2003**, *115*, 3784; *Angew. Chem. Int. Ed.* **2003**, *42*, 3656. .
[15] N. Solin, J. Kjellgren, K. J. Szabó, *J. Am. Chem. Soc.* **2004**, *126*, 7026.
[16] O. A. Wallner, K. J. Szabó, *Org. Lett.* **2004**, *6*, 1829.
[17] N. Solin, O. A. Wallner, K. J. Szabó, *Org. Lett.* **2005**, *7*, 689.
[18] O. A. Wallner, V. J. Olsson, L. Eriksson, K. J. Szabó, *Inorg. Chim. Acta* **2006**, *359*, 1767.
[19] A. Goliaszewski, J. Schwartz, *J. Am. Chem. Soc.* **1984**, *106*, 5028.
[20] A. Goliaszewski, J. Schwartz, *Tetrahedron* **1985**, *41*, 5779.
[21] M. Méndez, J. M. Cuerva, E. Gómez-Bengoa, D. J. Cárdenas, A. M. Echavarren, *Chem. Eur. J.* **2002**, *8*, 3620.
[22] M. Albrecht, G. v. Koten, *Angew. Chem.* **2001**, *113*, 3866; *Angew. Chem. Int. Ed.* **2001**, *40*, 3. .
[23] J. T. Singleton, *Tetrahedron* **2003**, *59*, 1837.
[24] M. E. v. d. Boom, D. Milstein, *Chem. Rev.* **2003**, *103*, 1759.
[25] J. Dupont, C. S. Consorti, J. Spencer, *Chem. Rev.* **2005**, *105*, 2527.
[26] J. Dupont, M. Pfeffer, J. Spencer, *Eur. J. Inorg. Chem.* **2001**, 1917.
[27] I. P. Beletskaya, A. V. Cheprakov, *J. Organomet. Chem.* **2004**, *689*, 4055.
[28] K. J. Szabó, *Synlett* **2006**, 811.
[29] R. B. Bedford, S. M. Draper, P. N. Scully, S. L. Welch, *New J. Chem.* **2000**, *24*, 745.
[30] H. Rimml, L. M. Venanzi, *J. Organomet. Chem.* **1983**, *259*, C6.
[31] M. W. Haenel, S. Oevers, J. Bruckmann, J. Kuhnigk, C. Krüger, *Synlett* **1998**, 301.
[32] D. M. Grove, G. v. Koten, J. N. Louwen, J. G. Noltes, A. L. Spek, H. J. C. Ubbels, *J. Am. Chem. Soc.* **1982**, *104*, 6609.
[33] Y. Yamamoto, N. Asao, *Chem. Rev.* **1993**, *93*, 2207.
[34] S. E. Denmark, J. Fu, *Chem. Rev.* **2003**, *103*, 2763.
[35] R. A. Fernandes, A. Stimac, Y. Yamamoto, *J. Am. Chem. Soc.* **2003**, *125*, 14133.
[36] T. Gastner, H. Ishitani, R. Akiyama, S. Kobayashi, *Angew. Chem.* **2001**, *113*, 1949; *Angew. Chem. Int. Ed.* **2001**, *40*, 1896. .
[37] D. Ferraris, T. Dudding, B. Young, W. J. Drudy, T. Lectka, *J. Org. Chem.* **1999**, *64*, 2168.
[38] X. Fang, M. Johannsen, S. Yao, N. Gathergood, R. C. Hazell, K. A. Jorgensen, *J. Org. Chem.* **1999**, *64*, 4844.
[39] R. A. Batey, A. N. Thadani, D. V. Smil, A. J. Lough, *Synthesis* **2000**, 990.
[40] S. Sebelius, V. J. Olsson, K. J. Szabó, *J. Am. Chem. Soc.* **2005**, *127*, 10478.
[41] F. Miyazaki, K. Yamaguchi, M. Shibasaki, *Tetrahedron Lett.* **1999**, *40*, 7379.
[42] W. Strohmeier, F.-J. Müller, *Chem. Ber.* **1967**, *100*, 2812.
[43] C. A. Tolman, *J. Am. Chem. Soc.* **1970**, *92*, 2953.
[44] A. D. Becke, *J. Chem. Phys.* **1993**, *98*, 5648.
[45] T. H. Dunning, P. J. Hay, *Modern Theoretical Chemistry, Vol. 3*, Plenum, New York, **1977**.
[46] P. J. Hay, W. R. Wadt, *J. Chem. Phys.* **1985**, *82*, 270.
[47] P. J. Hay, W. R. Wadt, *J. Chem. Phys.* **1985**, *82*, 299.
[48] Gaussian 03 (Revision B.04), M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, J. A. Montgomery, T. Vreven, K. N. Kudin, J. C. Burant, J. M. Millam, S. S. Iyengar, J. Tomasi, V. Barone, B. Mennucci, M. Cossi, G. Scalmani, N. Rega, G. A. Petersson, H. Nakatsuji, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, M. Klene, X. Li, J. E. Knox, H. P. Hratchian, J. B. Cross, C. Adamo, J. Jaramillo, R. Gomperts, R. E. Stratmann, O. Yazyev, A. J. Austin, R. Cammi, C. Pomelli, J. W. Ochterski, P. Y. Ayala, K. Morokuma, G. A. Voth, P. Salvador, J. J. Dannenberg, V. G. Zakrzewski, S. Dapprich, A. D. Daniels, M. C. Strain, O. Farkas, D. K. Malick, A. D. Rabuck, K. Raghavachari, J. B. Foresman, J. V. Ortiz, Q. Cui, A. G. Baboul, S. Clifford, J. Cioslowski, B. B. Stefanov, G. Liu, A. Liashenko, P. Piskorz, I. Komaromi, R. L. Martin, D. J. Fox, T. Keith, M. A. Al-Laham, C. Y. Peng, A. Nanayakkara, M. Challacombe, P. M. W. Gill, B. Johnson, W. Chen, M. W. Wong, C. Gonzalez, J. A. Pople, Gaussian, Inc., Pittsburgh, PA, **2003**.

Received: March 22, 2006
Published online: June 26, 2006

