Electronic and Steric Ligand Effects on the Activity and Regiochemistry in the Heck Reaction

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The cationic phenylpalladium(II)diimine catalyst has been systematically substituted, both in a symmetrical and in an unsymmetrical manner, using Me, t-Bu, OMe, and F groups. The effects of these substitutions on the insertion aptitude and regioselectivity of propene have been investigated using DFT calculations. For symmetrical substitutions, a correlation has been found between the stability of the catalyst HOMO and the insertion barrier: a stable HOMO leading to a comparatively low barrier of insertion. In the case of unsymmetrical substitutions of F and OMe, trans-influences led to relatively large differences in insertion aptitudes. Steric effects were notable when t-Bu replaced hydrogen at the nitrogen positions, primarily through the interaction between t-Bu and alkene methyl groups. Insertion barriers ranged from 9.3 to 13.7 kcal/mol. There was a general preference for 1,2-insertions. The regioselectivity, $\Delta\Delta E = E^*(2,1) - E^*(1,2)$, was in most cases modest (<1 kcal/mol). None of the investigated substitution patterns led to 2,1-insertion and only the unsymmetrical positioning of t-Bu improved the 1,2-insertion preference significantly.

Introduction

The migratory insertion of an alkene into a M−R bond represents a central step in catalytic processes such as polymerization[1] and oligomerization[2] of alkenes and the Heck reaction.[3,4] Because of its importance in synthetic organic chemistry, the Heck-type reaction has been thoroughly studied since its discovery in the late 1960s. The scope and limitations of the reaction have been reviewed in a number of recent articles.[5] Palladium is the metal of choice for Heck arylation reactions, although other metals have been employed on occasion, e.g., copper, rhodium, and nickel. However, none of them is as versatile as palladium.[5d] Phosphine-based ligands[6] have traditionally been employed, but a fair number of ligand systems with metal coordinating atoms other than phosphorus have been reported. Phenanthrolines[7] and carbene-type ligands[8,9] have been studied as well as mixed ligand systems such as P−N,[10] C−N,[11] P−C−P,[12] and S−C−S.[13] Underligated and nonligated palladium systems have also been investigated.[5d]

Despite extensive studies into Heck chemistry, few general, systematic trends can be found with regard to reactivity and selectivity. A serious problem is the control of regiochemistry in the addition to unsymmetric alkenes. Some success in regiocontrol has been achieved by the use of alkenes attached to an auxiliary coordinating group.[14] This is also true for the use of special ligands and acrylate or styrene as substrates.[15,16] We have initiated theoretical studies concerning the influence of steric and electronic effects on the activity and the regiochemistry in the Heck reaction. In previous work we have explored how the electronic properties of substituted alkenes affect the insertion barrier and the regiochemistry of migratory insertion into the Pd−R

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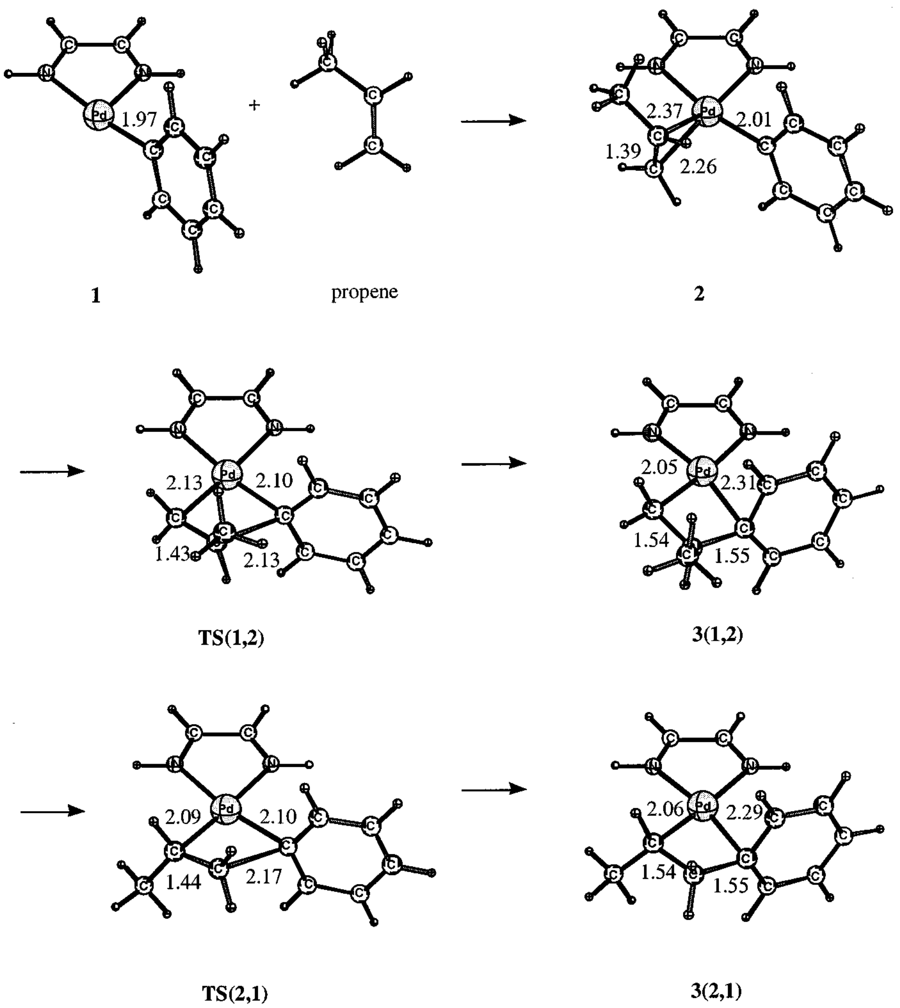

Figure 1. Representative structures of the π-coordination of propene and the successive migratory insertion into the phenyl–Pd bond. Structure **3** represents an intermediary product in the complete Heck reaction, stabilized by aryl–palladium π-interaction.

bond (R = $-CH_3$ and $-C_6H_5$).[17] A simple diimine ligand backbone (HN=CH–CH=NH) coordinated to the metal center was used as the model catalytic species. In general, electron-rich alkenes coordinated more strongly to the phenylpalladium(II) diimine complex, whereas electron-poor alkenes insert more readily. In this paper we present a parallel investigation into the effects of substitutions in the diimine backbone. All four possible positions (R_1–R_4, as shown in Figure 2) have been substituted in order to modify electronic as well as steric properties of the ligand system. Propene has been used as reacting alkene, and the influence on activity and regiochemistry has been studied.

Computational Details

Geometries and energies of all intermediates and transition states were fully optimized using the gradient-corrected hybrid density functional method B3LYP.[18] We used a basis set of double-ζ valence quality labeled LANL2DZ in the Gaussian98 program.[19] For Pd the core electrons were replaced by a relativistic electron core potential (ECP) developed by Hay and Wadt.[20] For nonmetal atoms the double-ζ basis sets of Huzinaga and Dunning were assigned.[21] All relative energies were recalculated using a valence triple-ζ quality basis set at the B3LYP level. For all nonmetal atoms the 6-311G(d,p) basis set[22] was employed, and for Pd the primitive LANL2DZ basis set was recontracted to 4s4p3d and an f-function (1.472) was added. The atomic charges were calculated using the Merz–Singh–Kollman scheme as implemented in Gaussian98.[23] It should be noted that calculations are commonly more reliable in studying trends than providing absolute numbers for a specific reaction, although modern calculations have shown to afford remarkably accurate figures also in absolute terms for migratory insertions.[24]

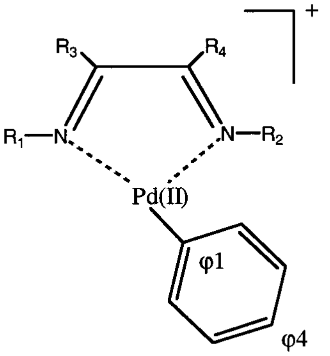

Figure 2. Positions R_1 to R_4 of the cationic phenylpalladium(II) diimine complex were systematically substituted with Me, t-Bu, F, and OMe groups.

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Results and Discussion

A range of substituted phenylpalladium(II) diimine catalysts have been studied in order to primarily elucidate the effects on the activity and regiochemistry in the Heck reaction. The regioselectivity is determined by the relative energy difference between the two possible insertion pathways, $\Delta\Delta E = \Delta E^*(2,1) - \Delta E^*(1,2)$, as illustrated in Figure 1. The palladium(II) diimine was systematically substituted with groups affecting the electronic and steric properties of the catalyst, according to Figure 2. The standard configuration is $R_1-R_4 = H$, with deviations from this structure noted in the tables.

To probe electronic effects, the substituents have been chosen to be typically electron donating (OMe) and typically electron withdrawing (F). Alkyl substituents such as Me and t-Bu can be considered to be electron donating, although the steric influence of these groups will mainly be the focus of this work. The relative complexation energies for propene coordinating to the different cationic phenylpalladium(II) diimine catalysts and the activation energies for the subsequent insertion into the phenyl−palladium bond are presented in Table 1.[25]

***π*-Coordination.** Propene coordinates to the catalyst with its double bond essentially perpendicular to the ligand plane, as shown in Figure 1. According to the Chatt−Dewar−Duncanson model,[26,27] the π-coordination strength of propene will depend on two components: one of σ character where the Pd atom accepts electrons from the filled π-orbital of the olefin, and one component of π character where Pd back-donates electrons into the of the π* antibonding orbital of the C═C bond. Therefore, the relative stabilities of the LUMO and the HOMO of structure **1** influence the π-coordination energy, $\Delta E(\pi)$. The energies of the accepting and donating orbitals of the variants of structure **1** are given in Table 2.

Table 1. Relative Energies of the π-Complexation and the Activation Energy of Insertion of Propene into the Pd−Ph Bond

entry	subst.	$\Delta E(\pi)$[a]	$\Delta E^*(2,1)$[b]	$\Delta E^*(1,2)$[c]	$\Delta\Delta E$[d]
1	H	−30.1	11.6	11.0	0.6
2	$R_1,R_2 = Me$	−27.7	11.5	10.9	0.6
3	$R_3,R_4 = Me$	−29.5	12.3	11.8	0.5
4	$R_1,R_2 = t\text{-}Bu$	−23.4	13.7	12.3	1.4
5	$R_3,R_4 = t\text{-}Bu$	−28.2	11.9	11.9	0.0
6	$R_1,R_2 = OMe$	−27.5	11.5	11.4	0.1
7	$R_3,R_4 = OMe$	−30.1	13.2	13.1	0.1
8	$R_1,R_2 = F$	−33.3	9.6	9.3	0.3
9	$R_3,R_4 = F$	−31.8	11.3	10.7	0.6
10	$R_1 = Me$	−28.5	11.9	10.8	1.1
11	$R_2 = Me$	−29.6	11.2	10.8	0.4
12	$R_1 = t\text{-}Bu$	−23.8	13.7	10.6	3.1
13	$R_2 = t\text{-}Bu$	−25.9	11.8	10.6	1.2
14	$R_1 = OMe$	−27.6	13.1	12.9	0.2
15	$R_2 = OMe$	−29.9	10.0	9.4	0.6
16	$R_1 = F$	−32.4	12.1	12.1	0.0
17	$R_2 = F$	−30.8	9.4	9.3	0.1

[a] $\Delta E(\pi)$ is the π-complexation energy of propene forming **2** in kcal/mol. [b] $\Delta E^*(2,1)$ is the reaction activation energy **2** → **TS(2,1)** in kcal/mol. [c] $\Delta E^*(1,2)$ is the reaction activation energy **2** → **TS(1,2)** in kcal/mol. [d] $\Delta\Delta E = \Delta E^*(2,1) - \Delta E^*(1,2)$, in kcal/mol.

Table 2. Energy of the Accepting LUMO and Donating HOMO of the Substituted Palladium(II) Diimine Catalysts 1

entry	subst.	E_{LUMO}[a]	E_{HOMO}[b]	$\Delta E(\pi)$[c]
1	H	−7.00	−11.01	−30.1
2	$R_1,R_2 = Me$	−6.83	−10.70	−27.7
3	$R_3,R_4 = Me$	−6.61	−10.58	−29.5
4	$R_1,R_2 = t\text{-}Bu$	−6.50	−10.32	−23.4
5	$R_3,R_4 = t\text{-}Bu$	−6.29	−10.24	−28.2
6	$R_1,R_2 = OMe$	−6.91	−10.75	−27.5
7	$R_3,R_4 = OMe$	−6.47	−10.37	−30.1
8	$R_1,R_2 = F$	−7.70	−11.72	−33.3
9	$R_3,R_4 = F$	−7.40	−11.38	−31.8
10	$R_1 = Me$	−6.85	−10.85	−28.5
11	$R_2 = Me$	−6.96	−10.85	−29.6
12	$R_1 = t\text{-}Bu$	−6.71	−10.69	−23.8
13	$R_2 = t\text{-}Bu$	−6.81	−10.62	−25.9
14	$R_1 = OMe$	−6.92	−10.90	−27.6
15	$R_2 = OMe$	−6.91	−10.82	−29.9
16	$R_1 = F$	−7.30	−11.34	−32.4
17	$R_2 = F$	−7.41	−11.38	−30.8

[a] Energy of the accepting LUMO of **1**, in eV. [b] Energy of the donating HOMO of **1**, in eV [c] $\Delta E(\pi)$ is the π-complexation energy of propene forming **2** in kcal/mol.

Entries 2−9 represent symmetrical substitutions of the simple ligand backbone (entry 1) and provide a starting point for the discussion of electronic and steric influences. Certain trends can be noted, observing the stability of the HOMOs and LUMOs. Electron-donating groups destabilize both the HOMO and LUMO. The π-coordination energy increases as the destabilization increases, and the effect is stronger for R_3, R_4 substitution than for R_1, R_2 substitution. This is nicely illustrated comparing the substitution patterns of Me and OMe. For symmetrical Me substitutions (entries 2 and 3), as the HOMO and LUMO are destabilized by 0.12 and 0.22 eV respectively, the π-coordination strength increases by 1.8 kcal/mol. The corresponding substitutions with OMe (entries 6 and 7) lead to a destabilization of the HOMO and LUMO by 0.38 and 0.44 eV, respectively, while the π-coordination strength increases by 2.6 kcal/mol. The π-coordination energy increases as both the HOMO and LUMO of the complex are destabilized, thus suggesting that the π-back-donation dominates the coordination of the olefin. Even though t-Bu

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(25) Cartesian coordinants of all presented structures are available as Supporting Information.

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is also electron donating and shows destabilizing effects on the HOMO and LUMO, steric interactions come into play with the coordination of propene that dominate the observed value of $\Delta E\pi$.

For electron-withdrawing substituents the picture is completely reversed. Both the HOMO and the LUMO are notably stabilized, especially when R_1,R_2 = F. Comparing entries 8 and 9, as the HOMO and LUMO are stabilized by 0.34 and 0.30 eV, respectively, the π-coordination strength increases by 1.5 kcal/mol. This implies that the σ-accepting orbital of Pd dominates the propene coordination in this case.

Unsymmetrical substitutions of F and OMe (entries 14−17) lead to some added complexity. The influences on the HOMO and LUMO of the substituted catalysts are the same as stated above. However, it can be seen that for both OMe (entries 14 and 15) and F (entries 16 and 17) the orbital energies are similar for substitution at R_1 and R_2, while the difference in π-coordination energy is notable. Comparing the energy of **2**, in the cases R_1 = OMe and R_2 = OMe, it is found that the structure where the phenyl is trans to the substituted nitrogen (R_1 = OMe) is thermodynamically preferred by 3.9 kcal/mol. Similarly, for F substitutions, the structure where R_1 = F is preferred by 3.8 kcal/mol over R_2 = F. The corresponding influence for Me (entries 10 an 11) is small.[28] We return to the subject of unsymmetrical substitution effects in more detail in the section below.

For the R_1 and R_2 positions steric influences can be observed as the size of substituents increases. Since the methyl group on propene in general is oriented away from the phenyl ring, substituting only at the R_1 position gives an indication of the interactions of propene with the catalyst ligand system. Substituting only at the R_2 position can also crowd the alkene in the π-coordination although indirectly, through the deflection of the phenyl ring. The π-coordination energy for R_1 = H is −30.1 kcal/mol, −28.5 kcal/mol for R_1 = CH_3, and −23.8 kcal/mol for R_1 = t-Bu. For R_2 substituents the π-coordination energy is −30.1 kcal/mol for R_2 = H, −29.6 kcal/mol for R_2 = CH_3, and −25.9 kcal/mol for R_2 = t-Bu. These results imply that steric interactions are significant when the substituent size becomes relatively large. Such effects were also found by Ziegler, investigating ethylene and propene polymerization with various substituted nickel(II) diimine and palladium(II) diimine catalysts.[24b,29] The role of the steric interaction was also illustrated by the fact that for R_1 = t-Bu propene was π-coordinated with the methyl group oriented toward the phenyl ring. Symmetrical substitutions of R_1 and R_2 give π-coordination strengths very similar to R_1 substitutions.

Migratory Insertion−Reaction Barrier. There are two regiochemical outcomes of insertion as depicted in Figure 1. Table 1 shows that 1,2-insertion is favored. For the simple catalyst (entry 1), the reaction barrier (**2** → **TS(1,2)**) is $\Delta E^*(1,2) = 11.0$ kcal/mol. The highest barrier for 1,2-insertion is 13.1 kcal/mol, found for R_3,R_4 = OMe, while the lowest barrier is 9.3 kcal/mol for R_1,R_2 = F. The trend for symmetrical substitutions is that electron-donating groups increase the barrier while electron-withdrawing groups lower it. A correlation between the stability of the HOMO and the insertion barrier can be observed, as shown in Figure 3, where an unstable HOMO leads to a high reaction barrier.

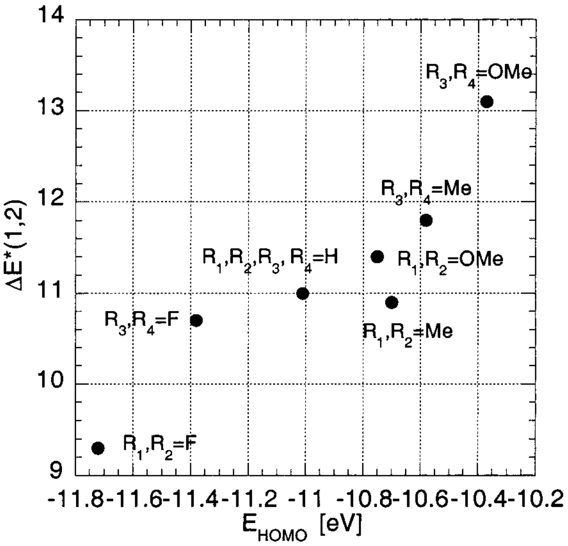

Figure 3. (a) HOMO energy [eV] of the phenylpalladium(II) diimine complex **1** vs insertion barrier [kcal/mol], **2** → **TS(1,2)**.

This relation can be rationalized by comparing the bonding situation of the π-coordination structure and the transition state. As can be seen in Figure 1, propene has to rotate, approximately 90° clockwise or counterclockwise, into the ligand plane, passing from **2** to **TS(1,2)** or **TS(2,1)**, respectively. A significant part of the reaction barrier will thus be due to the breaking of the π-back-donating component of the π-coordination of propene. A catalyst with an unstable HOMO will have a relatively strong π-back-donating component, leading to a higher reaction barrier. The σ-accepting component is by definition along the rotational axis and will not affect the reaction barrier to the same extent.

Table 1 shows some surprising features for unsymmetrical substitutions of F and OMe at the R_1 and R_2 positions. There is a marked difference in the reaction barrier when comparing R_1 and R_2 substitutions. The barrier for 1,2-insertion is 12.9 kcal/mol when R_1 = OMe and 9.4 kcal/mol when R_2 = OMe. The barrier of insertion is 12.1 kcal/mol when R_1 = F and 9.3 kcal/mol when R_2 = F. When R_1 = Me or R_2 = Me, the barrier for 1,2-insertion is the same, 10.8 kcal/mol.

Furthermore, as mentioned previously, F is expected to act in an electron-withdrawing manner, while OMe is expected to be electron-donating. Since neither F nor OMe has been observed to have any steric influence on the propene insertion, it is somewhat surprising to find similar results on the activation barrier. To get a clearer picture of the substituent effect on the metal-coordinating nitrogens, partial charges were derived from Mulliken population analysis (at the B3LYP/6-311G(d,p) level). The partial charges of N(1), N(2) and bond lengths Pd−N for **3(1,2)** structures are given in Table 3.

From Table 3 it is clearly seen that both F and OMe decrease the charge on the nitrogen when replacing hydrogen. The corresponding nitrogen coordination strength to palladium is also weakened, as can be noted from the increased Pd−N bond lengths. Substituting R_2

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[28] Structure **2**(R_1 = H, R_2 = Me) is preferred by 0.5 kcal/mol compared to **2**(R_1 = Me, R_2 = H).

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Table 3. Calculated Partial Charges and Selected Geometrical Parameters of Unsymmetrical Variants of Structure 3(1,2), as Well as the Calculated Thermodynamic Driving Force of the Insertion Step

subst.	$q_{N(1)}$[a]	$q_{N(2)}$[b]	Pd–N(1)[c]	Pd–N(2)[d]	$E_{\mathbf{3(1,2)}} - E_{\mathbf{2}}$[e]
$R_1,R_2 = H$	−0.42	−0.40	2.072	2.203	−10.5
$R_1 = Me$	−0.43	−0.41	2.106	2.183	−10.8
$R_2 = Me$	−0.43	−0.39	2.061	2.227	−9.8
$R_1 = OMe$	−0.21	−0.42	2.096	2.200	−7.9
$R_2 = OMe$	−0.42	−0.16	2.067	2.266	−12.6
$R_1 = F$	−0.13	−0.41	2.077	2.230	−8.6
$R_2 = F$	−0.43	−0.09	2.081	2.231	−14.2

[a] The partial charge at N(1) in au. [b] The partial charge at N(2) in au. [c] The distance Pd–N(1) in Å. [d] The distance Pd–N(2) in Å. [e] The thermodynamic driving force, $E_{\mathbf{3}} - E_{\mathbf{2}}$, forming the product **3(1,2)**, in kcal/mol.

$= H$ for $R_2 = OMe$ reduces the negative charge by 0.24 au at N(2) and increases the Pd–N(2) bond length by 0.06 Å. Substituting $R_2 = H$ for $R_2 = F$ reduces the negative charge by 0.31 au at N(2) and increases the Pd–N(2) bond length by 0.03 Å. A strongly bonded ligand, such as an aryl or alkyl, prefers to coordinate trans to weakly coordinated ligands. In a relative sense, this means that the intermediary products[9,17] **3**, where C_α is situated trans to the less strongly coordinated nitrogen, will be energetically more favorable. In the way the ligand backbone has been defined in this work, this implies that **3** will be more stable when $R_2 = F$ or $R_2 = OMe$.[30] The same influence has been noted above for the π-complexes **2**, with the important difference that placing the phenyl group trans to the substituted nitrogen ($R_1 = F$ or $R_1 = OMe$) gives the most stable structures. These energetic preferences are reflected in the thermodynamic driving force, e.g., $E_{\mathbf{3(1,2)}} - E_{(\mathbf{2})}$ (see Table 3). In the case of F substitution, the driving force is 5.6 kcal/mol larger for $R_2 = F$ compared to $R_1 = F$. This is in line with the 2.8 kcal/mol lower barrier for 1,2-insertion for $R_2 = F$ compared to $R_1 = F$. A similar effect has been reported for neutral salicylaldiminato nickel(II) complexes, polymerizing ethylene.[31]

Bulky substituents at the R_1 and R_2 positions affect the reaction barrier in an intuitive manner. The reaction barrier involving the most stable transition state, **TS-(1,2)**, is more or less unaffected by the increasing steric bulk at the R_1 position. The barrier is 11.0 kcal/mol for $R_1 = H$, 10.8 kcal/mol for $R_1 = CH_3$, and 10.6 kcal/mol for $R_1 =$ t-Bu. For this transition state the methyl group on propene is oriented toward the phenyl substituent, and therefore the steric influence from R_1 substituents on the energy of the TS is minimal. Not surprisingly, the influence of substituents on the stability of **TS(2,1)** is clearly affected by the size of the group at the R_1 position. The barrier is 11.6 kcal/mol for $R_1 = H$, 11.9 kcal/mol for $R_1 = CH_3$, and 13.7 kcal/mol for $R_1 =$ t-Bu.

Bulky substituents at the R_2 position seemingly leave the reaction barrier for $\mathbf{2} \rightarrow$ **TS(1,2)** unaffected. The barrier is 11.0 kcal/mol for $R_2 = H$, 10.8 kcal/mol for $R_2 = CH_3$, and 10.6 kcal/mol for $R_2 =$ t-Bu. The barrier for $\mathbf{2} \rightarrow$ **TS(2,1)** is 11.0 kcal/mol for $R_2 = H$, 11.2 kcal/mol for $R_2 = CH_3$, and 11.8 kcal/mol for $R_2 =$ t-Bu. However, for symmetrical substitutions of R_1, $R_2 =$ t-Bu, the reaction barrier **2-TS(2,1)** is the same as for $R_1 =$ t-Bu ($\Delta E^*(2,1) = 13.7$ kcal/mol), while $\Delta E^*(1,2) = 12.3$ kcal/mol for R_1, $R_2 =$ t-Bu, compared to 10.6 kcal/mol for $R_2 =$ t-Bu. This indicates that there is indeed a steric influence on the transition state through bulky groups at R_2. Such effects are not evident until steric bulk at R_1 also is present, restricting the flexibility of the transition state structure. The steric bulk of groups at R_2 crowds the phenyl ring, causing it to be deflected away from the R_2 substituent. The angle N(2)–Pd–$C_{\varphi 1}$ (see Figure 2) increases as follows: 96.8° for $R_2 = H$, 99.0° for $R_2 = CH_3$, 101.0° for $R_2 = OMe$, 102.9° for $R_2 = F$, and 108.4° for $R_2 =$ t-Bu. The tilt of the phenyl ring also changes slightly. The angle Pd–$C_{\varphi 1}$–$C_{\varphi 4}$ (see Figure 2) changes: 167.6° for $R_2 = H$, 167.3° for $R_2 = CH_3$, 165.6° for $R_2 = OMe$, 164.3° for $R_2 = F$, and 156.4° for $R_2 =$ t-Bu. Selected geometrical parameters are given in Table 4.

Migratory Insertion–Regiochemistry. The regiochemical selectivity of the migratory insertion is of central interest. The results show that 1,2-insertion is the favored insertion pathway (Table 1). Ignoring the results for t-Bu, where steric influences dominate, we find that all other investigated substitutions affect the selectivity only to a small extent. For the simple catalyst (entry 1), the preference for 1,2-insertion is 0.6 kcal/mol. The average preference for 1,2-insertion is 0.4 kcal/mol (standard deviation of 0.3 kcal/mol). The influence on the regioselectivity of different substitution patterns, symmetrical and unsymmetrical, for each substituent (Me, OMe, F) is also very small (=0.6 kcal/mol). From this we draw the conclusion that electronic effects play only a minor role in the regiochemical outcome for palladium(II) diimine catalysts.

As has been previously noted, stability of intermediates and transition state structures is clearly influenced by the presence of steric groups at the R_1 and R_2 positions. The selectivity increases as the size of the group at R_1 increases. This effect has also been observed by Ziegler, in palladium-catalyzed polymerization of propene.[29] The relative preference for 1,2-insertion is 0.6 kcal/mol for $R_1 = H$, 1.1 kcal/mol for $R_1 = CH_3$, and 3.1 kcal/mol for $R_1 =$ t-Bu. Influences of substituents at the R_2 position are small, and it is not immediately clear how the regiochemistry would be affected. However, as was discussed above, large substituents at R_2 deflect the phenyl ring, thereby crowding the transition states. The resulting effect on selectivity becomes clearer when comparing with the symmetrical substitutions at R_1, R_2. The best regiochemical selectivity ($\Delta\Delta E$) is observed for $R_1 =$ t-Bu, where $\Delta E^*(2,1)$ is 13.7 kcal/mol and $\Delta E^*(1,2)$ is 10.6 kcal/mol, i.e., $\Delta\Delta E = 3.1$ kcal/mol. When $R_1,R_2 =$ t-Bu, $\Delta E^*(2,1)$ is still 13.7 kcal/mol and $\Delta E^*(1,2)$ is now 12.3 kcal/mol. In this case $\Delta\Delta E$ is only 1.3 kcal/mol, and it is obvious that the effect of substituting t-Bu at R_2 is a destabilization of **TS(1,2)**. It is intuitive that crowding of the phenyl group should have a more pronounced effect on the transition state structure where the methyl group on propene is closest to the phenyl ring. A similar steric effect is hinted upon for the analogue Me substitutions, where $\Delta\Delta E$ is 1.1 kcal/mol when $R_1 = Me$ and $\Delta\Delta E = 0.6$ when $R_1,R_2 =$

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(30) A parallel effect is observed for unsymmetrical variants of **1**. **1**($R_1 = F$, $R_2 = H$) is thermodynamically favored over **1**($R_1 = H$, $R_2 = F$) by 2.1 kcal/mol. **1**($R_1 = OMe$, $R_2 = H$) is thermodynamically favored over **1**($R_1 = H$, $R_2 = OMe$) by 3.5 kcal/mol.

(31) Chan, M. S. W.; Deng, L.; Ziegler, T. *Organometallics* **2000**, 19, 2741

Table 4. Selected Geometrical Parameters of the Substituted Palladium(II) Diimine Catalysts 1

entry	subst.	Pd−$C_{\varphi 1}$	Pd−N(1)[b]	Pd−N(2)[c]	N−Pd−$C_{\varphi 1}$[d]	Pd−$C_{\varphi 1}$−$C_{\varphi 4}$[e]
1	H	1.972	2.217	2.049	96.8	167.6
2	R_1,R_2 = Me	1.975	2.205	2.076	98.7	167.6
3	R_3,R_4 = Me	1.977	2.187	2.035	96.0	170.8
4	R_1,R_2 = t-Bu	1.971	2.177	2.106	106.0	158.5
5	R_3,R_4 = t-Bu	1.983	2.136	2.006	98.5	169.0
6	R_1,R_2 = OMe	1.962	2.225	2.089	100.7	164.7
7	R_3,R_4 = OMe	1.974	2.204	2.055	95.6	171.3
8	R_1,R_2 = F	1.969	2.243	2.082	100.1	166.7
9	R_3,R_4 = F	1.964	2.278	2.090	97.9	165.8
10	R_1 = Me	1.973	2.228	2.039	96.9	168.0
11	R_2 = Me	1.972	2.194	2.085	99.0	167.3
12	R_1 = t-Bu	1.978	2.222	2.035	95.5	170.7
13	R_2 = t-Bu	1.967	2.164	2.140	108.4	156.4
14	R_1 = OMe	1.968	2.258	2.045	96.1	167.8
15	R_2 = OMe	1.968	2.189	2.089	101.0	165.6
16	R_1 = F	1.967	2.230	2.065	97.4	166.7
17	R_2 = F	1.964	2.218	2.080	102.9	164.3

[a] The distance in Å between the carbon of the phenyl group ($C_{\varphi 1}$) and Pd. [b] The distance in Å between the substituted diimine N(1) and Pd. [c] The distance Å between the substituted diimine N(2) and Pd. [d] The angle N(2)−Pd−$C_{\varphi 1}$. [e] The angle Pd−$C_{\varphi 1}$−$C_{\varphi 4}$.

Me. The differences are however very small in this case and could be due to other than steric effects.

It would be interesting to see if the most striking electronic and steric effects observed could be additive. We therefore examined an unsymmetrical diimine catalyst, where R_1 = t-Bu and R_2 = F, to see if we would get a low insertion barrier and good regioselectivity. The reaction barrier was indeed found to be low ($\Delta E^*(1,2) = 7.7$ kcal/mol) and the regioselectivity remained high, even improving somewhat ($\Delta\Delta E = 3.7$ kcal/mol). It is worth noting that for the activated catalyst **1** the steric bulk of t-Bu forces the phenyl ring to be trans to the nitrogen to which t-Bu is bonded, rather than trans to the nitrogen with F as substituent, which is preferred electronically.[32] Hereby, the t-Bu can have the optimal effect on the regioselectivity while F can have the optimal influence on the insertion barrier (driving force).

Conclusions

The (HN═CH−CH═NH) backbone of cationic phenylpalladium(II) diimine has been systematically substituted, both in a symmetrical and unsymmetrical manner, using Me, t-Bu, OMe, and F groups. Electronic influences were observed with respect to the insertion barrier. For symmetrical substitutions, a comparatively high energy of the catalyst HOMO correlated to a relatively high barrier of insertion. In the case of unsymmetrical substitutions of F and OMe, trans-influences led to fairly large differences in insertion aptitudes. For example, when R_1 = F the barrier for **2** → **TS(1,2)** was 2.8 kcal/mol lower than when R_2 = F, the difference being caused by decreased stability of **2** and increased stability of the product **3(1,2)**. Steric effects were notable only when the largest substituent (t-Bu) replaced hydrogen at the nitrogen positions. Effects on the insertion barrier and regioselectivity were primarily due to the interaction between t-Bu and alkene methyl groups. However, the presence of t-Bu at R_2 also led to steric repulsion of the phenyl ring. No clear electronic effect was observed on the regioselectivity of the reaction. The highest 1,2-preference ($\Delta\Delta E = 3.1$ kcal/mol) was observed for R_1 = t-Bu.

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Supporting Information Available: Cartesian coordinants of all presented structures. This material is available free of charge via the Internet at http://pubs.acs.org.

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(32) Structure **1**(R_1 = t-Bu, R_2 = F) is thermodynamically favored over **1**(R_1 = F, R_2 = t-Bu) by 0.8 kcal/mol. This should be compared with **1**(R_1 = H, R_2 = F) and **1**(R_1 = F, R_2 = H), where the thermodynamic stability is reversed; **1**(R_1 = F, R_2 = H) is more stable by 2.1 kcal/mol.