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Stereoselective homogeneous catalytic arylation of methyl methacrylate: Experimental and computational study

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ABSTRACT

Catalytic systems trans-[$PdCl_2(DEA)_2$]/DEA and trans-[$PdCl_2(DEA)_2$]/[DEA][HAc], used in the model reaction of methyl methacrylate with iodobenzene, 4-iodoanisole, and bromobenzene, provide homogeneous catalysis, good regioselectivity and excellent stereoselectivity. The major product of the regioselective reaction is internal olefin. In all examined cases the only stereoisomer of the internal olefin methyl 3-phenyl-2-methylpropenoate is the E-isomer, whereas the only stereoisomer of the double arylated reaction product methyl 2-benzyl-3-phenylpropenoate is the Z-isomer. A DFT study, which investigates mechanistic aspects of migratory insertion, β-hydride elimination and reductive elimination of this phosphine-free Heck reaction, is in agreement with our experimental findings.

1. Introduction

Among palladium-catalyzed reactions, the arylation and vinylation of alkenes, known as the Heck reaction, is one of the most important carbon–carbon bond forming processes [1–7]. This reaction has major impact on organic chemistry due to its significant synthetic versatility and possibility for countless complex organic molecules to be prepared [8–10]. Over the last two decades an impressive number of applications have been developed at the laboratory and industry. The Heck reaction becomes more interesting when the used alkene is disubstituted, what allows different regio- and stereoselectivity. To achieve synthesis of one regio- or stereoisomer of a trisubstituted alkene with high yield is still a challenge in modern synthetic organic chemistry. One of the most important and difficult targets is the control of the configuration of the double bond, the *E*- and *Z*-selectivity.

A lot of work has been devoted to the elucidation of the Heck reaction pathways where phosphines are used as ligands [11–18], whereas the results regarding non-phosphine ligands are scarce [19–22]. Mechanistically, the Heck reaction is a multistep organic reaction, whereby at least one intermediate contains σ carbon–metal bond. The Heck reaction mechanism, which can be anionic, cationic, or neutral, attracts attention of both experimental and theoretical chemists [23–37].

The preactivation reaction of a phosphine-free Heck reaction, where *trans*-dichlorobis(diethanolamine-*N*)palladium(II) complex (*trans*-[$PdCl_2(DEA)_2$]) was used as a precatalyst [30–32], has recently been elaborated. It was established that the catalytically active DEA–Pd(0)–Cl complex was obtained in the preactivation process [30–32]. The next step in the Heck catalytic cycle, oxidative addition of aryl halide to Pd(0) species, is considered a key step in the mechanism of Pd-mediated cross-coupling reactions, and usually involves coordinatively unsaturated Pd(0) complexes [11–16,34]. The reaction further proceeds through the migratory insertion and β-hydride transfer/reductive elimination steps [38–45].

The aim of this experimental and DFT study is to investigate possible ways of migratory insertion, β-hydride and reductive elimination of phosphine-free Heck reaction, where a disubstituted alkene methyl methacrylate is used as a substrate. In the Heck reaction of aryl halides with methyl methacrylate, biologically active and useful trisubstituted olefins with broad applications in pharmaceutical industry (for example α-methylcinnamates) can be obtained. These compounds show interesting physico-chemical properties, too. In order to provide sustainable green homogeneous catalysis, beside DEA as solvent, the ionic liquid (IL) diethanolammonium acetate ([DEA][HAc]) was also used as reaction medium.

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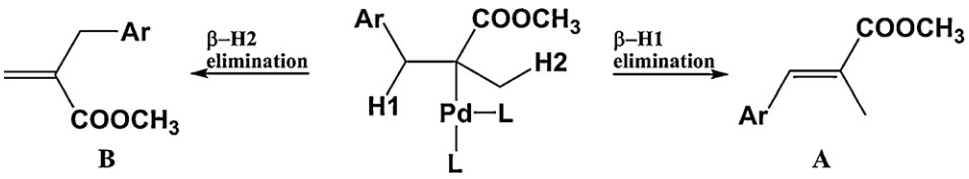


Scheme 1. β-hydride elimination in 1,1-disubstituted olefins.

2. Experimental

2.1. Materials

The reactions were monitored and analyzed with GC chromatography and ^{1}H NMR spectroscopy. The GC analyses were performed on an Agilent 6890N (G 1530N) instrument (Serial # CN10702033), with capillary apolar column. The ^{1}H NMR spectra were run in $CDCl_3$ on a Varian Gemini 200 MHz spectrometer. For column chromatography silica gel 60 (Merck, particle size 0.063–0.200 mm) was used. The compounds $PdCl_2$, diethanolamine, aryl iodides, bromobenzene and methyl methacrylate were obtained from Aldrich Chemical Co.

2.2. General procedure for the Heck reaction

Corresponding aryl halide (1.05 mmol), methyl methacrylate (1 mmol), DEA (1.0 ml), or ([DEA][HAc]) (1.0 ml), and $PdCl_2$ (1.5 mol%) were placed in 25-ml flask, and stirred at 110 °C for 12 and 24 h. The mixture was cooled to room temperature. The reaction products (*E*-methyl 3-phenyl-2-methylpropenoate (**a**), methyl 2-benzylpropenoate (**b**) and *Z*-methyl 2-benzyl-3-phenylpropenoate (**c**)) were separated from the reaction mixture by extraction and decantation with diethyl ether/hexane (5:1). The combined organic layer was washed with water and brine, dried with Na_2SO_4, and evaporated under the reduced pressure. The reactions were monitored and analyzed with ^{1}H NMR and GC. It appeared that the orange *trans*-[$PdCl_2(DEA)_2$] complex was formed after ten minutes of heating the reaction mixture, in both reaction media – DEA or [DEA][HAc] [30,46]. The reaction products were purified by column chromatography (silica gel; pethrolether/ethylacetate (8:1) for the mixture of **a** and **b**, and with pethrolether/ethylacetate (2:1) for **c**). After the extraction of the product of the first-time reaction, the solvent residue of the Heck reaction was washed with C_2H_5OH (3 ml) and Et_2O (3 ml × 3 ml), and dried under the reduced pressure. After this treatment, the catalyst/DEA or catalyst/[DEA][HAc] system can be reused directly without further purification [46].

The reaction products were analyzed and characterized on the basis of their ^{1}H NMR spectroscopic data, and by comparing these data to the literature data [47,48] and spectra of the commercially available compounds. The ^{1}H NMR spectrum of the mixture of **a** and **b**, as well as that of **c**, are presented in Supplementary Data.

2.3. Computational methods

The geometrical parameters of all stationary points and transition states were optimized with Gaussian09 [49], using the CPCM model, and diethanolamine as solvent (ε = 25.75). All calculations were performed using the M06 functional [50]. This hybrid meta functional is a method with good accuracy "across-the-board" for transition metals, main group thermochemistry, medium-range correlation energy, and barrier heights [50]. The triple split valence basis set 6-311 + G(d,p) was used for C, H, O, N, and Cl, whereas LANL2DZ + ECP [51] was employed for the Pd and I centers. All calculated structures were confirmed to be local minima (all real vibrational frequencies) for equilibrium structures, or first-order saddle points (one imaginary vibrational frequency) for transition state structures, by frequency calculations. The intrinsic reaction coordinates (IRCs), from the transition states down to the two lower energy structures, were traced using the IRC routine in Gaussian, in order to verify that each saddle point is linked with two putative minima. The natural bond orbital analysis (Gaussian NBO version) was performed for all structures.

3. Results and discussion

In our previous studies we established that $PdCl_2$ upon heating in DEA or [DEA][HAc] produced an orange solution, from which a yellow-orange substance crystallized [30,46,52]. The NMR and IR spectra, as well as elemental analysis, showed that the structure of the obtained crystal substance corresponds to that of *trans*-[$PdCl_2(DEA)_2$] complex. The crystal structure of *trans*-[$PdCl_2(DEA)_2$] was provided in [52], whereas its electronic structure was presented in [31]. The *trans*-[$PdCl_2(DEA)_2$] complex appeared to be very efficient in the Heck coupling reaction of different aryl halides with nonsubstituted acrylates, in the presence of strong and weak base [30,34], and ILs [46].

In order to test catalytic efficiency of this complex in the Heck reaction with a 1,1-disubstituted olefin, a model reaction with methyl methacrylate was performed. The reaction conditions provided in situ formation of *trans*-[$PdCl_2(DEA)_2$]. We were particularly focused on the impact of the complex, base (which also acts as reaction medium), and reaction time on the regio- and stereoselectivity of such reaction. It is known that the choice of base can affect the products distribution and rate of the Heck reaction. The combinations of K_2CO_3 and DMF as solvent, NaOAc and Bu_3N in DMAc, and bulky tertiary amine Cy_2NMe in dioxane have been used in various earlier attempts to carry out efficient synthesis of stereo- and regiodefined trisubstituted olefins [47,53,54]. In our homogeneous catalytic protocol DEA and [DEA][HAc] played role of reaction media, bases, and precatalyst-precursors. Iodobenzene, 4-iodoanisole, and bromobenzene were used for arylation of methyl methacrylate.

In the Heck reaction with methacrylates two possible pathways for double-bond formation (β-hydride elimination) are possible: the first pathway yields the expected trisubstituted (internal) *E*/*Z* olefin **A**, and the other one leads to the formation of 1,1-disubstituted (terminal) olefin **B** (Scheme 1) [55].

In our model reaction the mixtures of three olefins (**a**, **b**, and **c**, Fig. 1) were observed, whereby the internal olefin **a** was the major product of the regioselective reaction (Table 1). Taking into account that the olefin **b** suffers further Heck reaction yielding the diarylated olefin **c**, it can be concluded that the best regioselectivity was achieved in the reaction with 4-iodoanisole in DEA or [DEA][HAc], after 24 h (**a**:**b** + **c** = 5:2.5). The regioselectivity of the reactions with iodobenzene and bromobenzene was somewhat lower. The yield of the diarylated product **c** was the highest in the reaction with iodobenzene, after prolongation of reaction time from 12 h to 24 h. It should be pointed out that in all cases the only stereoisomer of the internal olefin **a** is the *E*-isomer, whereas the only stereoisomer of the double arylated product **c** is the *Z*-isomer. The stereoselec-

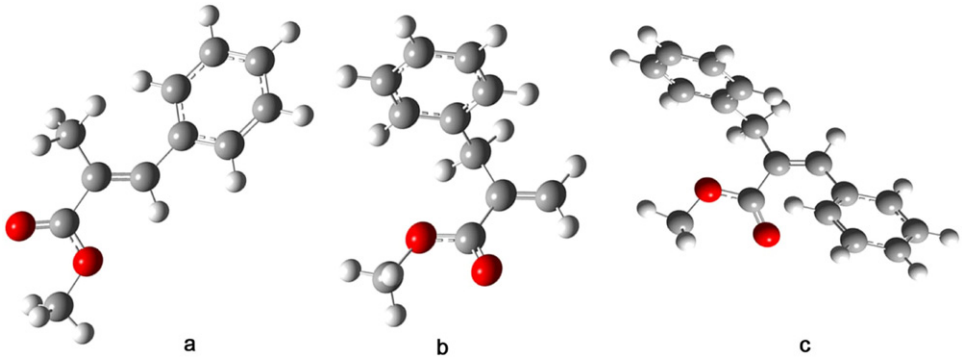


Fig. 1. Optimized geometries of the Heck reaction products **a**, **b**, and **c**.

tivity was determined on the basis of the ^{1}H NMR spectra of the isolated products.

The catalytic system IL–Pd remains unchanged during the homogeneous catalytic reaction (orange color of the reaction mixture, no palladium black) [46]. It seems that the nature of the used IL increases the stability of the palladium catalyst, extending its lifetime. Catalyst and products of this reaction can be easily separated via simple extraction and decantation from the reaction mixture. Although it is clear that the used catalytic systems *trans*-[$PdCl_2(DEA)_2$]/DEA and *trans*-[$PdCl_2(DEA)_2$]/[DEA][HAc] are effective in the Heck homogeneous catalysis, little is known about mechanistic details of such reactions.

This fact provoked us to investigate possible mechanistic pathways for migratory insertion, β-hydride and reductive elimination, using DFT method. The mechanisms of these relevant steps in the Heck reaction of methyl methacrylate with all aryl substrates used in our experiments (iodobenzene, 4-iodoanisole, and bromobenzene) are mutually very similar. For this reason, we here present the mechanism of the reaction with iodobenzene, whereas the other two reactions are presented in Supplementary Data.

3.1. DFT study of the model reaction

As previously postulated [34] the oxidative addition of iodobenzene to the catalytically active DEA–Pd(0)–Cl complex yields two possible intermediates (**1** and **2** in Scheme 2).

One can assume that migratory insertion begins with olefin coordination to **1** or **2**. Let us consider the HOMO map of methyl methacrylate and LUMO map of 1 (Fig. 2), as well as their NBO charges. The HOMO map delineates the most electron sufficient area in methyl methacrylate (double bond), while the LUMO map depicts the most electron deficient area in **1** (Pd atom). The NBO charges on Pd, and C2 and C3 of methyl methacrylate amount 0.17, −0.30, and −0.12, respectively. These facts support possible coordination of methyl methacrylate to **1**. The obtained complex **3** is *trans* coordinated (Scheme 2). As known in literature [18] *trans* complex **3** isomerizes into the less stable (by 3 kJ/mol), but catalytically active, *cis* complex **3**.

One can suppose that the Pd–N coordinative bond in **2** is particularly weak, due to the *trans* effect [56–58]. This assumption is supported by the NBO analysis of **2**, which shows that there is a very weak donation of density from the lone pair on N (sp^3 orbital) to two formally empty p orbitals of Pd. As a consequence, the neutral DEA ligand can be easily substituted with methyl methacrylate [38,39], thus forming *cis*-**3**.

cis-**3** exhibits square planar coordination. The NBO analysis of this complex reveals that Pd is spd^2 hybridized. It forms two covalent (with C1 and iodine) and two coordinative (C2–C3 π orbital and chlorine) bonds. Low occupancy in σ Pd–C1 (1.81) and σ Pd–I (1.88) orbitals is a consequence of mutual delocalization of each bonding orbital into the adjacent σ^* antibonding orbital. Pd possesses four lone electron pairs in the d orbitals, where one of them shows a low occupancy of 1.86. This electron pair delocalizes into the π^* antibonding C2–C3 orbital, whereas the C2–C3 π orbital delocalizes into the formally empty, almost pure p orbital of Pd. There is a strong donation of density from the lone pair of Cl (sp^3 orbital) to the formally empty p orbital of Pd.

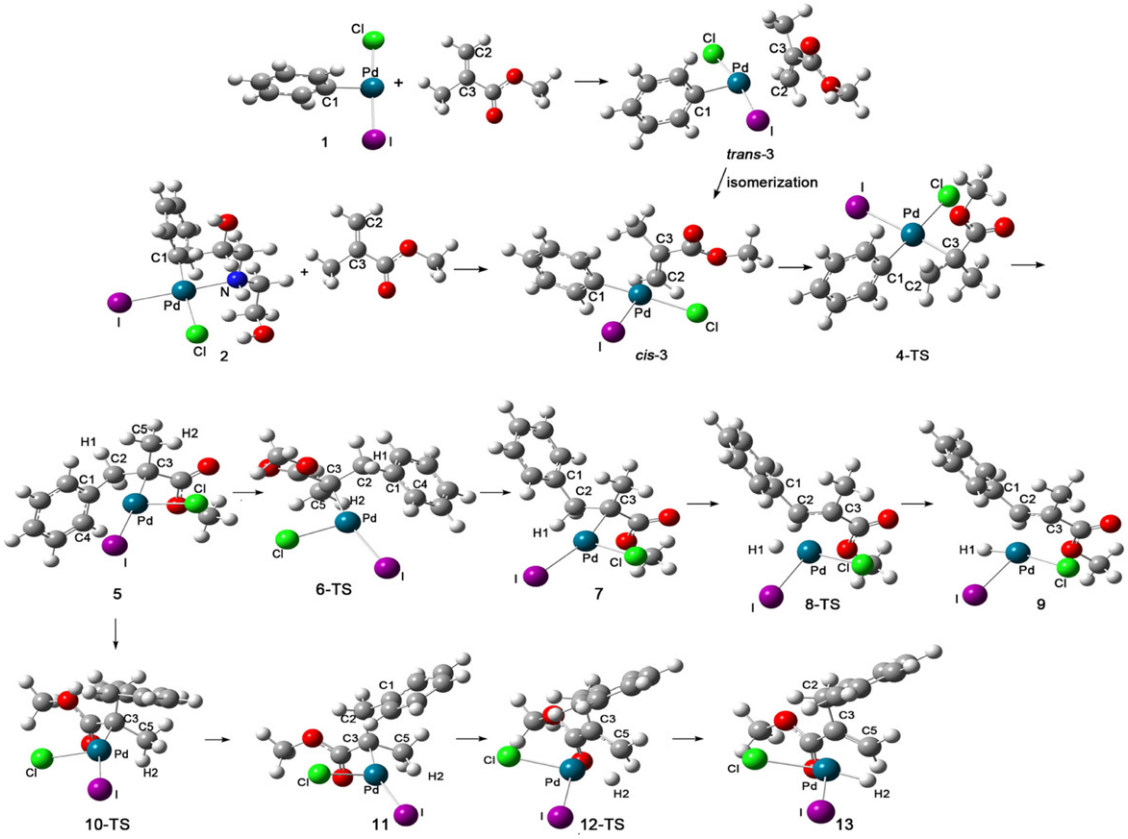
The next reaction step is the formation of the new C1–C2 bond, with simultaneous cleavage of the σ Pd–C1 bond. This step occurs via transition state **4-TS** (Scheme 2), which requires activation energy of 45.4 kJ/mol, and yields the complex **5**, the final intermediate in the migratory insertion step. The NBO analysis of **5** reveals that Pd forms only one covalent σ bond (Pd–C3), and three coordinative bonds (with Cl, I, and π C1–C4 orbital). It is worth pointing out that coordinative interaction of Pd with π C1–C4 bond is particularly weak.

5 can undergo β-hydrogen elimination in two possible ways: one is β-elimination of H1, and the other is β-elimination of H2 (Scheme 2). Bearing in mind the reaction conditions (increased temperature), and the fact that the coordinative interaction between Pd and π C1–C4 orbital is very weak, it is reasonable to expect that **5** can isomerize into agostic complexes, which are characterized by the presence of hypovalent three-center two-electron bonds [59,60]. Our investigations show that the structures of the agostic complexes **7** and **11** are appropriate for β-hydride elimination [18,61,62]. These complexes are formed from **5** via transition states **6-TS** and **10-TS** (Scheme 2), and require the activation energies of 29.4 and 26.5 kJ/mol, respectively. In **7** Pd forms three covalent bonds – with C3, Cl and I, whereas in **11** Pd forms just two

Table 1
Palladium-catalyzed arylation of methyl methacrylate.

Entry	Aryl halide[a]	Solvent	Time (h)	Products ratio[b] **a**:**b**:**c**
1	C_6H_5I	DEA	12	2.5:1:1
2	C_6H_5I	DEA	24	4:1:2
3	C_6H_5I	[DEA][HAc]	12	3.5:1:1
4	C_6H_5I	[DEA][HAc]	24	5.5:1:2
5	$CH_3OC_6H_4I$	DEA	12	2.5:1:0.8
6	$CH_3OC_6H_4I$	DEA	24	5:1:1.5
7	$CH_3OC_6H_4I$	[DEA][HAc]	12	3:1:1
8	$CH_3OC_6H_4I$	[DEA][HAc]	24	5:1:1.5
9	C_6H_5Br	DEA	12	2.5:1:1
10	C_6H_5Br	DEA	24	3:1:1
11	C_6H_5Br	[DEA][HAc]	12	3:1:1
12	C_6H_5Br	[DEA][HAc]	24	3.5:1:1

[a] About 85% of bromobenzene and 4-iodoanisole, and about 95% of iodobenzene were converted to the reaction products.
[b] The products ratio determined by GC and their isolated amounts.



Scheme 2. Possible pathways for migratory insertion, β-hydride elimination and reductive elimination of the catalytic arylation of methyl methacrylate with iodobenzene.

covalent (with C3 and I), and one coordinative (with Cl) bonds. H1 in **7** and H2 in **11** are directed toward Pd, thus enabling the formation of three-center two-electron C—H—Pd bonds. The existence of the C2—H1—Pd three-center two-electron bond is confirmed by the NBO analysis [63] of **7**. Namely, σ C2—H1 bond delocalizes into the formally empty sp^3 orbital of Pd. As a consequence, the occupancy in the formally empty orbital of Pd equals 0.10, and the C2—H1 bond in **7** is by 0.08 Å longer than the corresponding bond in **5**. Similarly, there is C5—H2—Pd three-center two-electron bond in isomer **11**. Here, σ C5—H2 orbital donates density to the formally empty sp^3 orbital of Pd, thus increasing its occupancy (0.10), and elongating the C6—H2 bond by 0.07 Å in comparison to the corresponding bond in **5**.

Our numerous attempts to reveal a reaction path for possible isomerization between **7** and **11** were unsuccessful. In addition, we were not able to locate a transition state for the formation of the agostic complex whose β-hydride elimination would lead to the *Z* product. We suppose that the isomerization is hindered by the presence of the methyl group. On the other hand, the structure of this complex was optimized (Fig. S1). The complex is apparently significantly strained, and consequently, its free energy is by 10.5 and 8.8 kJ/mol higher than those of **7** and **11**. These results are in accord with the experimentally determined stereoselectivity of the reaction.

In the further course of the reaction, the β hydrogens (H1 and H2) undergo transfers from the corresponding carbon atoms (C2

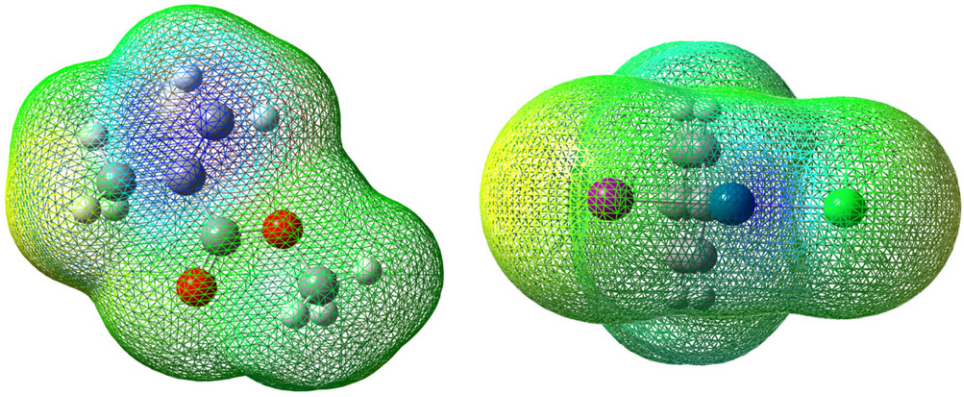


Fig. 2. HOMO map of methyl methacrylate (left) and LUMO map of **1**. The regions where the values of the HOMO and LUMO are greatest are indicated in blue. In the grayscale image, the darker regions (around double bond and palladium) depict the greatest values of the HOMO and LUMO. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

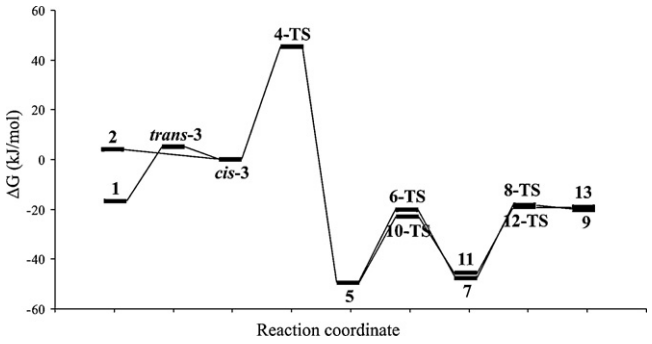


Fig. 3. The free energy profile of the migratory insertion and β-hydride elimination steps in the arylation of methyl methacrylate with iodobenzene.

in **7** and C5 in **11**) to the Pd center (Scheme 2). These steps of the reaction proceed via **8-TS** and **12-TS** transition states, and require the activation energies of 28.9 and 26.7 kJ/mol, respectively. In both transition states, C—H bond is completely broken, while new Pd—H bond is being established. In addition, a new π bond between carbon atoms (C2—C3 in **8-TS** and C3—C5 in **12-TS**) is being formed. The products of this reaction step are intermediates **9** and **13**. In these intermediates, Pd forms covalent bonds with I and H, and coordinative bonds with Cl and π orbital (C2—C3 in **9**, and C3—C5 in **13**).

The free energy profile of the migratory insertion and β-hydride elimination steps is depicted in Fig. 3. The diagram shows that the rate determining step is the formation of the new C1—C2 bond, which occurs via **4-TS**. Other two pairs of transition states (**6-TS** and **10-TS**; **8-TS** and **12-TS**) require mutually very similar activation energies, which are noticeable lower than that for the formation of **4-TS**. It can be concluded that relatively low activation energies for **6-TS**–**12-TS** enable both reaction paths, leading to the formation of **9** and **13**, and further of **a** and **b**.

Due to the *trans* effect, the coordinative interactions with π orbitals are particularly weak, implying that **9** and **13** are susceptible to ligand substitution. As DEA is available in the reaction mixture, it coordinates to Pd, thus forming complex **14** (Fig. 4) and liberating the products **a** and **b** (Fig. 1). Our investigation shows that **a** is more stable than **b** (by 15.7 kJ/mol for the reactions with iodobenzene and bromobenzene, and by 22.0 for the reaction with 4-iodoanisole). The relative stabilities of the products **a** and **b** are in agreement with the found product ratios. Namely, the regioselectivity is higher in the case of the reaction with 4-iodoanisole in comparison to that with iodobenzene and bromobenzene (Table 1). In addition, Table 1 shows that the ratio **a**:**b** + **c** increases with the prolonged reaction time. These facts, as well as relatively low and very similar activation energies needed for the formation of **a** and **b**, indicate that the investigated reaction is thermodynamically controlled. Our finding is different from that of Ambrogio et al., who have investigated the Heck reaction of aryl iodides and bromides with allyl ethers, and found that the reaction is kinetically controlled [36]. The difference in reaction mechanisms is probably due to the reaction conditions, as well as different chemical nature of the used substrates.

The structure of **14** is very similar to those of the complex intermediates whose reductive elimination has already been investigated [30–32]. Thus, one can suppose that **14** will also undergo reductive elimination. Since the most electron sufficient area in **14** involves iodine (Fig. 4), it is reasonable to expect that HI will be liberated, and catalytically active Pd(0) complex will be recovered. This assumption was confirmed by revealing the transition state **15-TS** (Fig. 4), which requires activation energy of 75.6 kJ/mol.

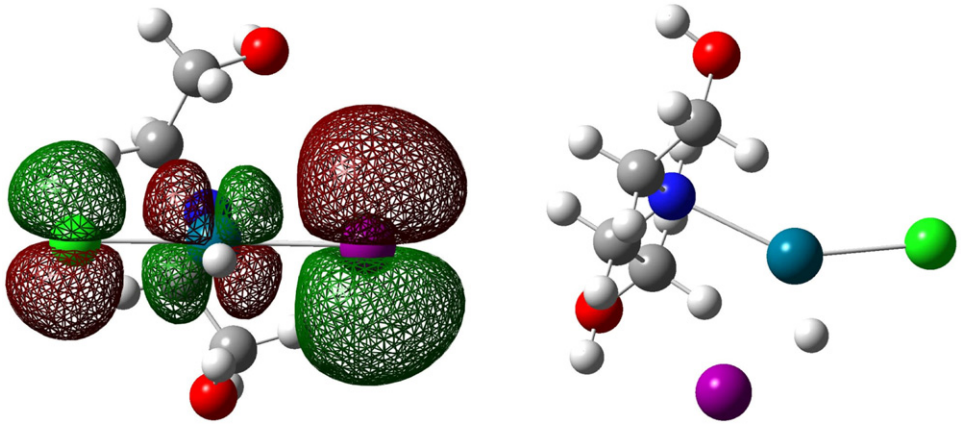


Fig. 4. Optimized structures of **14** (left), and **15-TS** (right). The HOMO of **14** is depicted.

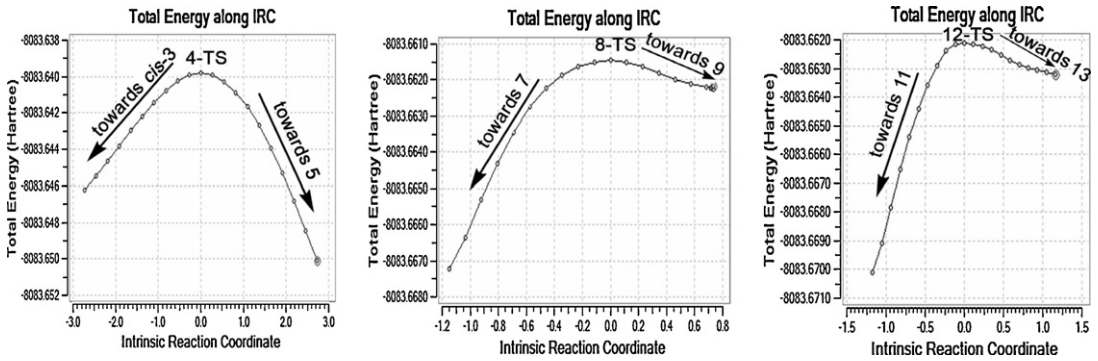
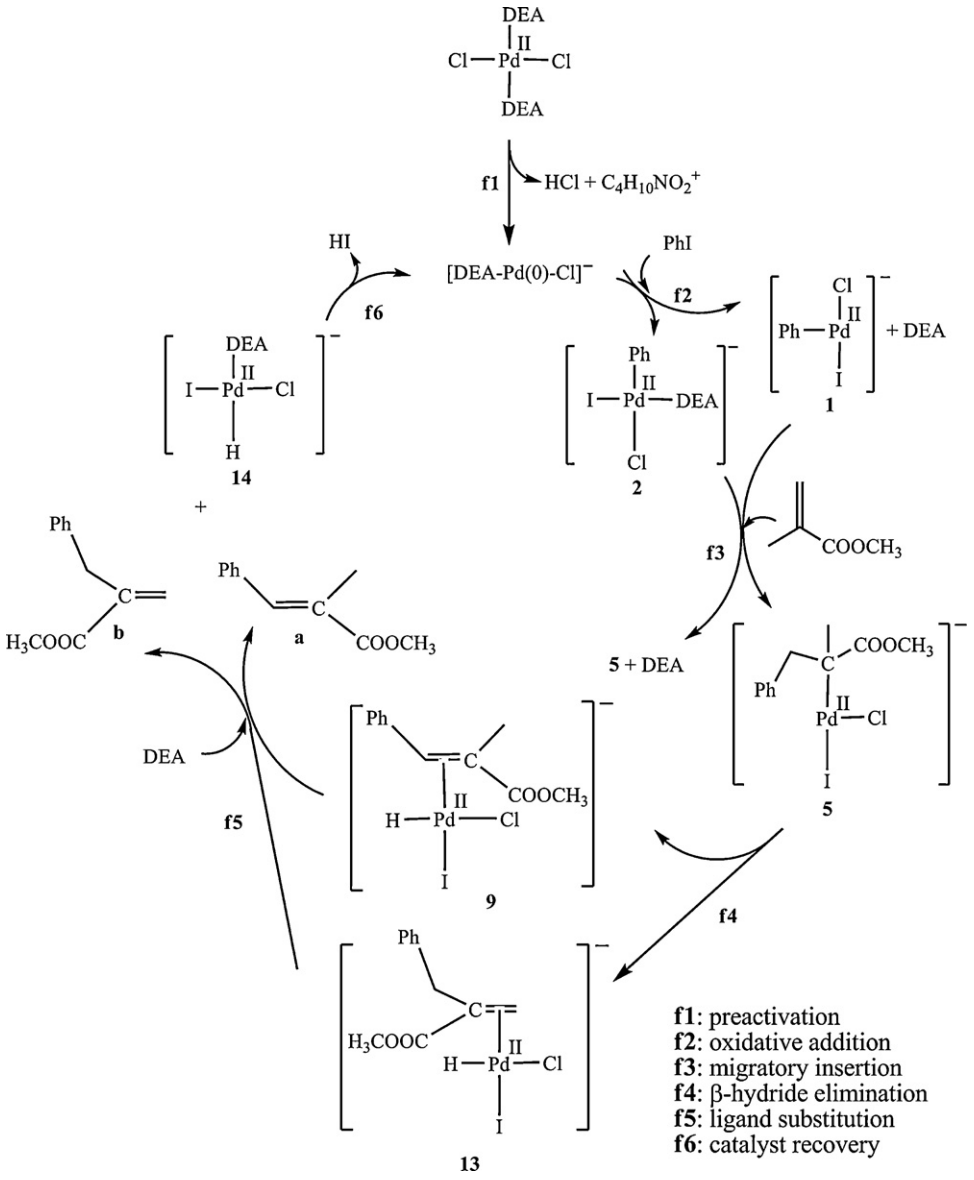


Fig. 5. The results of the IRC calculations for **4-TS** (left), **8-TS** (middle), and **12-TS** (right).



Scheme 3. Full catalytic cycle for the Heck reaction performed with $PdCl_2$ and methyl methacrylate in DEA.

Table 2
The energetics of the catalytic cycle for the reaction performed with $PdCl_2$ and methyl methacrylate in DEA.

f1 [30,31]		ΔG = 584.8 kJ/mol E_a = 111.8 kJ/mol
f2 [34]	$[DEA-Pd(0)-Cl]^- + PhI \rightarrow \mathbf{1} + DEA$ $[DEA-Pd(0)-Cl]^- + PhI \rightarrow \mathbf{2}$	$\Delta G = -169.0$ kJ/mol E_a = 17.1 kJ/mol $\Delta G = -194.5$ kJ/mol E_a = 50.7 kJ/mol
f3	$\mathbf{1} + \text{methyl methacrylate} \rightarrow \mathbf{5}$ $\mathbf{2} + \text{methyl methacrylate} \rightarrow \mathbf{5} + DEA$	$\Delta G = -32.9$ kJ/mol $\Delta G = -53.6$ kJ/mol
f4	$\mathbf{5} \rightarrow \mathbf{9}$ $\mathbf{5} \rightarrow \mathbf{13}$	ΔG = 29.8 kJ/mol E_a = 29.4 kJ/mol ΔG = 30.6 kJ/mol E_a = 26.5 kJ/mol
f5	$\mathbf{9} + DEA \rightarrow \mathbf{14} + \mathbf{a}$ $\mathbf{13} + DEA \rightarrow \mathbf{14} + \mathbf{b}$	ΔG = 28.0 kJ/mol ΔG = 43.0 kJ/mol
f6	$\mathbf{14} + DEA \rightarrow [DEA-Pd(0)-Cl]^- + [HDEA][I]$	ΔG = 40.0 kJ/mol E_a = 75.6 kJ/mol

In **15-TS** the Pd—H and Pd—I bonds are being cleaved, and the new H—I bond is being formed. It is worth pointing out that the electronic pair from the Pd—H bond remains on Pd, implying that Pd(II) is reduced to Pd(0). In this way, the catalytically active $[DEA–Pd(0)–Cl]^-$ complex is recovered. The liberated HI is captured by DEA, yielding the salt [DEAH][I].

The Pd(0) complex undergoes oxidative addition [34], and further reaction with **b** (as it has a terminal double bond), conforming the same mechanism as other 1,1-disubstituted alkenes, and yielding **c** (Fig. 1). Mechanistic pathways for migratory insertion, β-hydride elimination, and reductive elimination with **b** as a substrate are examined, and presented in Supplementary Data.

The results of the IRC calculations for transition states **4-TS**, **8-TS**, and **12-TS** are presented in Fig. 5.

This paper examines migratory insertion, β-hydride and reductive elimination in the Heck reaction of methyl methacrylate and some aryl halides. Taking into account our results on the preactivation reaction [30–32], and oxidative addition [34], now we are able to present the full catalytic cycle for the reaction performed with $PdCl_2$ and methyl methacrylate in DEA (Scheme 3). Table 2 provides the energetics of the catalytic cycle.

The preactivation step is pronouncedly endothermic, and requires the highest activation energy in the overall Heck reaction. As for the catalytic cycle, oxidative addition and migratory insertion are exothermic, whereas β-hydride elimination, ligand substitution, and reductive elimination (catalyst recovery) are endothermic. The overall catalytic cycle is slightly exothermic, and the highest activation barrier is needed for the reductive elimination step.

4. Conclusion

Catalytic systems *trans*-$[PdCl_2(DEA)_2]$/DEA and *trans*-$[PdCl_2(DEA)_2]$/[DEA][HAc], used in the reaction of methyl methacrylate with aryl halides, provide sustainable homogeneous catalysis, good regioselectivity and excellent stereoselectivity. In all cases the only stereoisomer of the internal olefin methyl 3-phenyl-2-methylpropenoate is the *E*-isomer, whereas the only stereoisomer of the double arylated reaction product methyl 2-benzyl-3-phenylpropenoate is the *Z*-isomer. Our DFT study is in agreement with this experimental finding. Namely, possible isomerization of **5** to an intermediate whose transformation would lead to *Z*-methyl 3-phenyl-2-methylpropenoate would be hindered by the presence of the methyl group. There is similar steric hindrance that prevents the formation of *E*-methyl 2-benzyl-3-phenylpropenoate (possible isomerization to an appropriate intermediate would be hindered by the presence of the benzyl group). In both cases the geometries of these intermediates, suitable for β-hydride elimination, would be extremely strained.

Our experiments show that, in all examined cases, the internal olefin **a** is the major product of the regioselective reaction. This finding is in agreement with our DFT investigation. Namely, the activation barriers for the formation of **a** and **b** are relatively low and mutually very similar, and their influence to the products distribution is poor. On the other hand, **a** is thermodynamically more stable than **b**, and thus, **a** is the preferred reaction product.

Our anionic Heck protocol allows efficient separation of the catalyst and reaction products from the reaction mixture (via simple extraction and decantation), in contrast to many other homogeneous catalyses, where it is a significant problem.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.molcata.2012.01.007.

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