Benzoquinone-Induced Stereoselective Chloride Migration in (η^3-Allyl)palladium Complexes. A Theoretical Mechanistic Study Complemented by Experimental Verification

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Benzoquinone-mediated Cl^- migration reactions in (η^3-allyl)palladium complexes were studied using density functional theory at the B3PW91 level. *p*-Benzoquinone coordinates to palladium in an η^2 fashion, exerting considerable steric and electronic effects which facilitate the ligand migration. Studies involving the commercially available benzoquinone derivatives chloranyl, fluoranyl, and 2,3-dichloro-5,6-dicyanobenzoquinone (DDQ) show that the activation barrier to the ligand migration can be decreased by employing electron-withdrawing substituents on benzoquinone. Benzoquinone derivatives with large π-acceptor ability and moderately bulky substituents induce ligand migration most effectively. Alkyl substitution of the allyl moiety also lowers the activation energy for Cl^- migration. The lowest activation barrier was encountered for an [η^3-(1,2,3)-cyclohexenyl]palladium complex coordinated to DDQ. Experimental studies verified that, in such types of complexes, Cl^- migration is feasible, providing stereodefined 3-chlorocyclohexene products. Since benzoquinone-mediated ligand migration in (η^3-allyl)palladium complexes is a key step in synthetically important palladium-catalyzed transformations, the implications of the theoretical results are discussed for the *cis*-migration of other ligands and for the inductive ability of different benzoquinone derivatives.

1. Introduction

Allylpalladium chemistry is one of the most successful areas of homogeneous catalysis.[1] In particular, palladium-catalyzed allylic substitution and allylic oxidation reactions have proved to be very useful preparative methods.[2−4] One of the most important aspects of this type of chemistry is the possibility of controlling the chemo-, regio-, and stereoselectivity of the nucleophilic attack on the allyl moiety through the choice of reaction conditions and the ancillary ligands on palladium.[5,6] Recently the development of asymmetric catalysis proceeding through chiral (η^3-allyl)palladium intermediates has received considerable attention.[7,8] Isolation and investigation of the (η^3-allyl)palladium intermediates of the catalytic reactions has offered a good opportunity to understand the nature of the interactions that govern the stereo- and enantioselectivity in the key reaction step.[9−12]

However, in certain catalytic transformations, such as in allylic oxidation[13] of alkenes and in 1,4-oxidation of conjugated dienes,[14,15] the key intermediates are not stable enough for direct kinetic or structural investigation. In these reactions, *p*-benzoquinone (BQ) is usually used as a cocatalyst, as it has two important functions in the catalytic cycle: (1) oxidation of palladium(0) to palladium(II) to maintain the catalytic cycle and (2) coordination to palladium to activate the (η^3-allyl)-palladium intermediate to nucleophilic attack.[12,16,17] Employment of BQ is also important to accomplish high regio- and stereoselectivity in these reactions. Replacement of BQ with other cocatalysts leads to a decrease of the stereoselectivity and sometimes even the regioselectivity of the catalytic transformations.[14,18]

Since attempts to isolate (η^3-allyl)palladium−BQ complexes have remained unsuccessful, fundamental knowledge about the mode of coordination of BQ to palladium and the importance of steric interactions and

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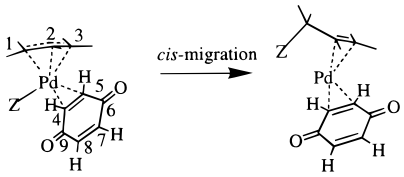
electronic effects on the reactivity of the (η^3-allyl)-palladium−BQ complex is unavailable. Nevertheless, such information would be very important in obtaining a better understanding of the mechanism of BQ-induced nucleophilic attack and particularly the stereoselective *cis*-migration of nucleophiles in (η^3-allyl)palladium complexes (eq 1). The *cis*-migration is the key step in



(1)

preparatively useful palladium-catalyzed 1,4-oxidation of dienes and allylic oxidation of olefins, which are suitable for the synthesis of stereodefined alkenes and heterocyclic compounds.[13−15,19,20]

In particular, mechanistic information on the migration aptitude of the coordinated ligand (Z in eq 1) as a function of the electronic and steric effects of BQ would be of significant help for furthering the development of allylic oxidation reactions. Previous experimental studies showed that several nucleophiles (e.g., acetate) readily migrate to the allyl moiety in the presence of BQ,[12,16] while other nucleophiles, such as Cl^-, do not migrate at all. Migration of chloride is particularly difficult to accomplish using standard activating ligands (e.g., phosphines), because this nucleophile has a large coordination affinity to palladium.[21] Hence, experimental data reported on Cl^- migration in (η^3-allyl)palladium complexes are rather scarce. The only example that could be found in the literature was published by Bäckvall and co-workers on $CuCl_2$-assisted chloride migration from palladium to allylic carbon.[18]

Since (η^3-allyl)palladium−BQ complexes cannot be studied directly by experiment, a theoretical investigation of these species can provide valuable information about their structure and reactivity. Because of the considerable interest presently in investigating those electronic and steric interactions that govern the reactivity and selectivity in palladium-mediated catalytic transformations, several high-level theoretical studies have very recently appeared, discussing the nucleophilic attack on (η^3-allyl)palladium complexes.[22−24] However, mechanistic investigation of the key reaction step in palladium catalyzed allylic oxidation of alkenes and 1,4-oxidation of conjugated dienes requires explicit consideration of the steric and electronic effects of the BQ auxiliary. Since Cl^- is the simplest available species for internal nucleophilic attack in synthetically useful palladium-catalyzed oxidation reactions, in the present study the migration of the Cl^- nucleophile in (η^3-allyl)-palladium−BQ complexes will be investigated. Furthermore, studies on the migration of the Cl^- nucleophile are particularly interesting from a preparative point of view, since commonly used BQ derivatives have not been able to induce Cl^- migration in (η^3-allyl)-palladium complexes. Considering that (η^3-allyl)palladium-Cl(L) complexes form readily from alkenes, dienes, and other easily available starting materials,[3] it would be of great synthetic importance to find BQ derivatives that are able to induce *cis*-migration of chloride and other nucleophiles with low migration aptitude.

2. Computational Methods

The geometries of **1**−**7** were fully optimized employing a Becke-type[25] three-parameter density functional model, B3PW91. This so-called hybrid functional includes the exact (Hartree−Fock) exchange, the gradient corrected exchange functional of Becke,[26] and with the more recent correlation functional of Perdew and Wang.[27] All calculations were carried out using a double-ζ (DZ) + P basis set constructed from the LANL2DZ basis,[28−30] which includes relativistic effective core potentials for palladium, by adding one set of d polarization functions to the heavy atoms and a diffuse d-function to palladium.[31,32]

Geometry optimization of the complexes representing minima on the potential energy surface (such as **1a**−**7a**, **1c**−**7c**) was performed by Schlegel's Berny algorithm in redundant internal coordinates.[33] The search for transition state (TS) structures (**1b**−**7b**) was done by the syncronous transit-guided quasi-Newton (STQN) method,[33,34] which was suitable to provide geometries reasonable close to the TS structures. However, a final convergence could not be accomplished by this method; hence, the final optimization of the TSs was performed in Cartesian coordinates with the Berny method, using B3PW91/3-21G second derivative matrix for an initial estimation of the force constants.

Since calculation of the harmonic frequencies required for characterization of the stationary points and calculation of zero-point vibration corrections is computationally prohibitive with the LANL2DZ+P basis set, the frequency calculations were done by employing a smaller basis set: 3-21G, preceded by reoptimization of the geometries. In a recent publication, Cotton and Feng[35] pointed out that fairly good geometries and frequencies can be obtained for second row transition metal complexes by using this basis set in connection with hybrid functionals.

The charges were calculated from the B3PW91/LANL2DZ+P densties using the natural bond orbital (NBO) analysis method of Weinhold and co-workers.[36,37]

3. Results and Discussion

The B3PW91/LANL2DZ+P geometrical parameters, energies, and NBO charges of **1**−**7** calculated in this work are given in Figure 1, and the calculated activation energies are displayed in Figure 2.

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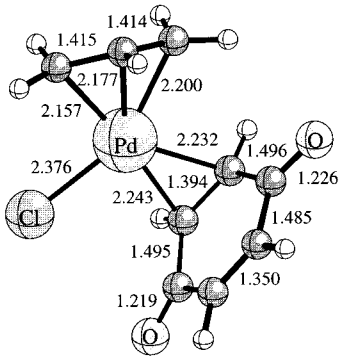
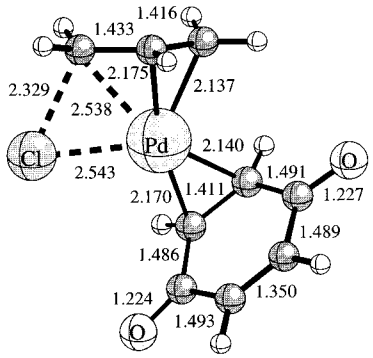
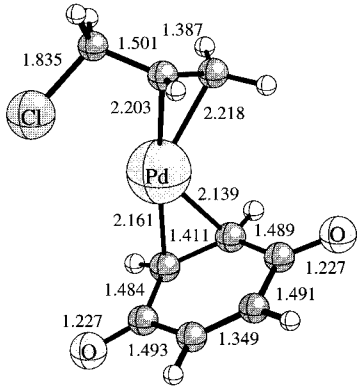


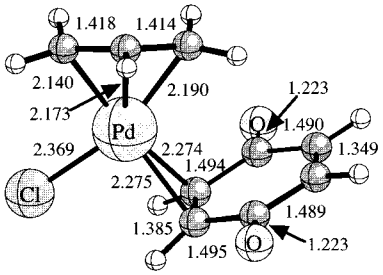
1a, ΔE = 0, *0*



1b, ΔE = 15.3, *15.0*



1c, ΔE = 2.4, *2.5*



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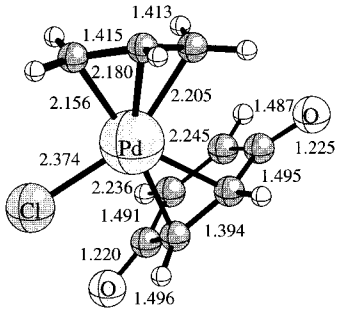
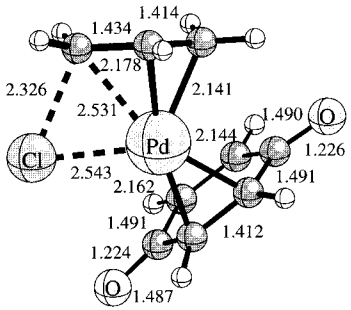
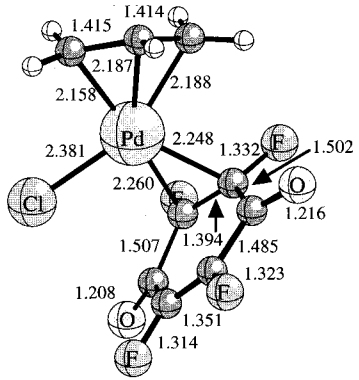


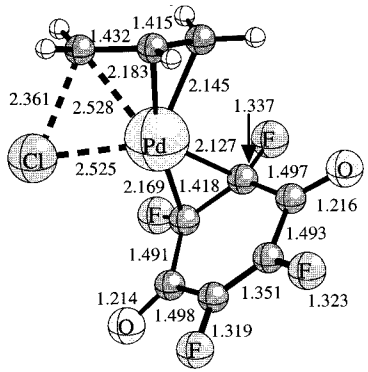
1e, ΔE = 0.4



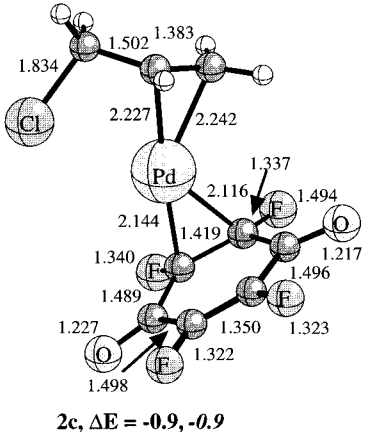
1f, ΔE = 15.7



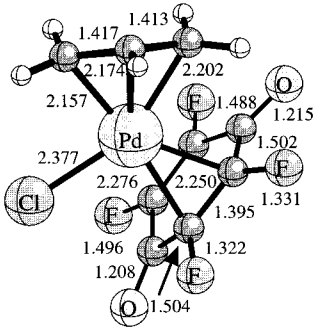
2a, ΔE = 0, *0*



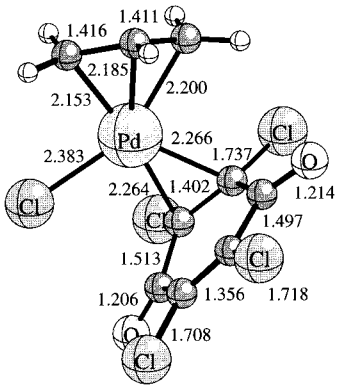
2b, ΔE = 13.6, *13.2*



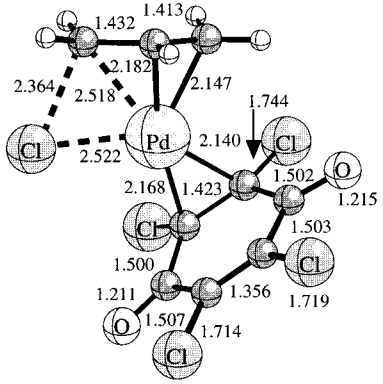
2c, ΔE = -0.9, *-0.9*



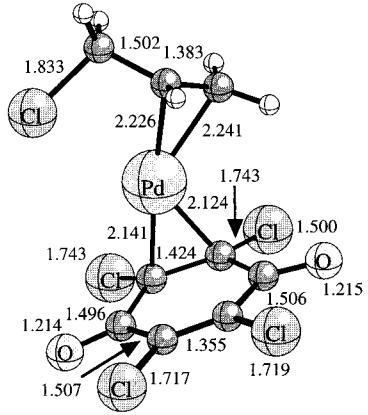
2d, ΔE = 0.9, *0.9*



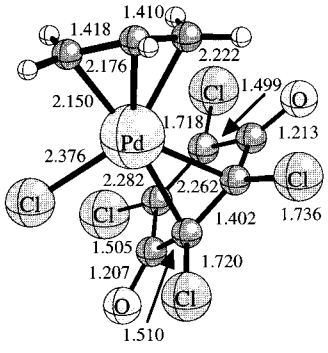
3a, ΔE = 0, *0*



3b, ΔE = 12.5, *12.3*



3c, ΔE = -2.5, *-2.3*



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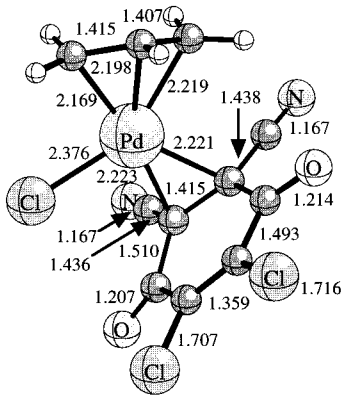
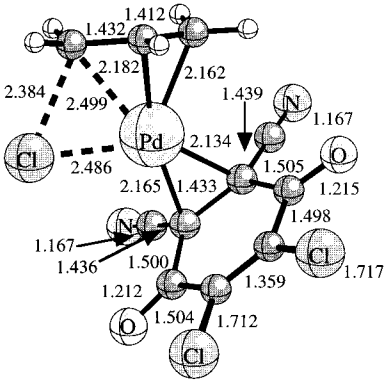
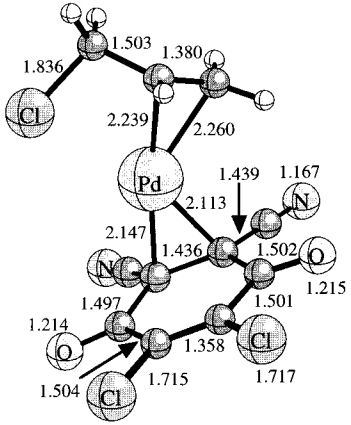


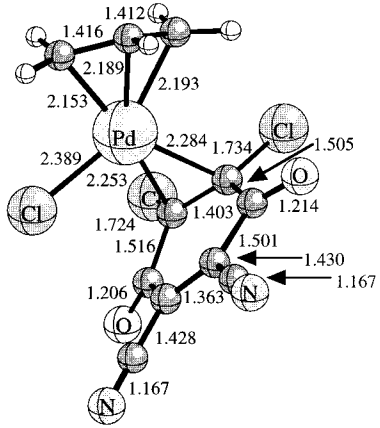
4a, ΔE = 0, *0*



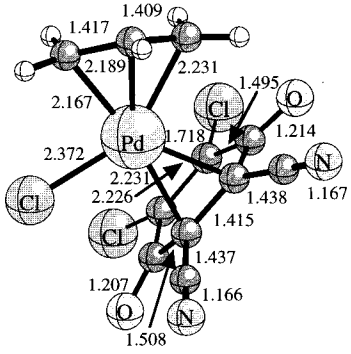
4b, ΔE = 10.1, *9.9*



4c, ΔE = -5.7, *-5.4*



4d, ΔE = 3.4



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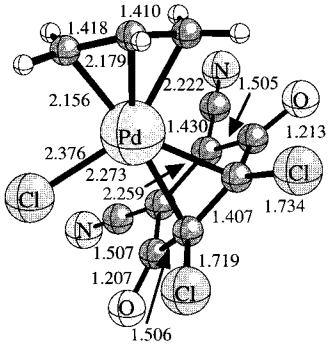

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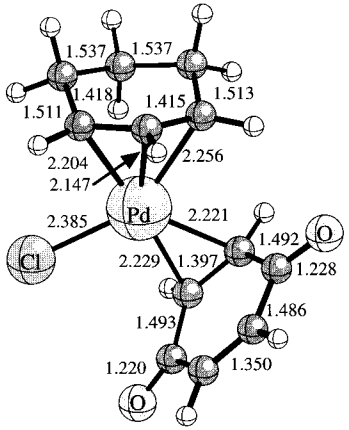
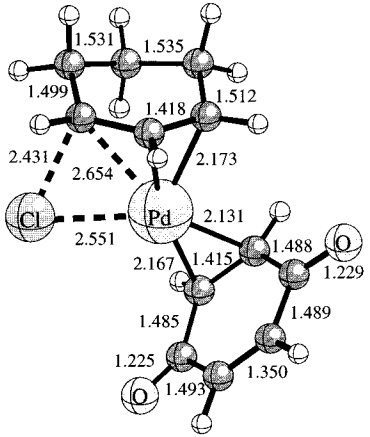


5a, ΔE = 0



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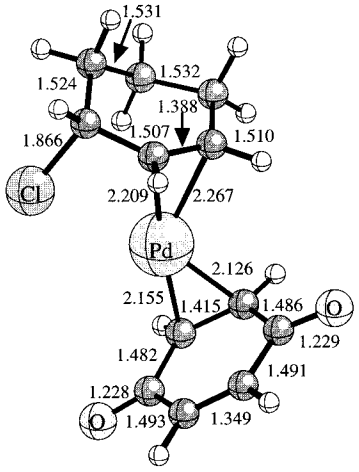

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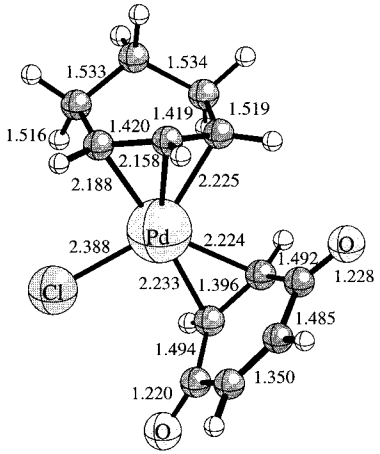

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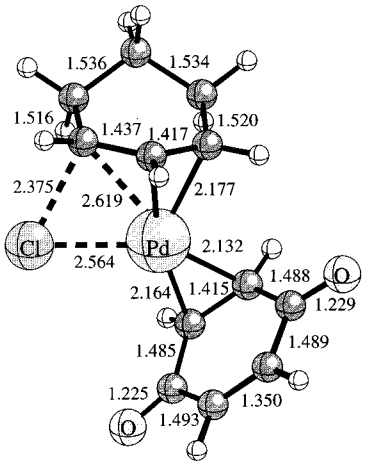

6b, ΔE = 15.9

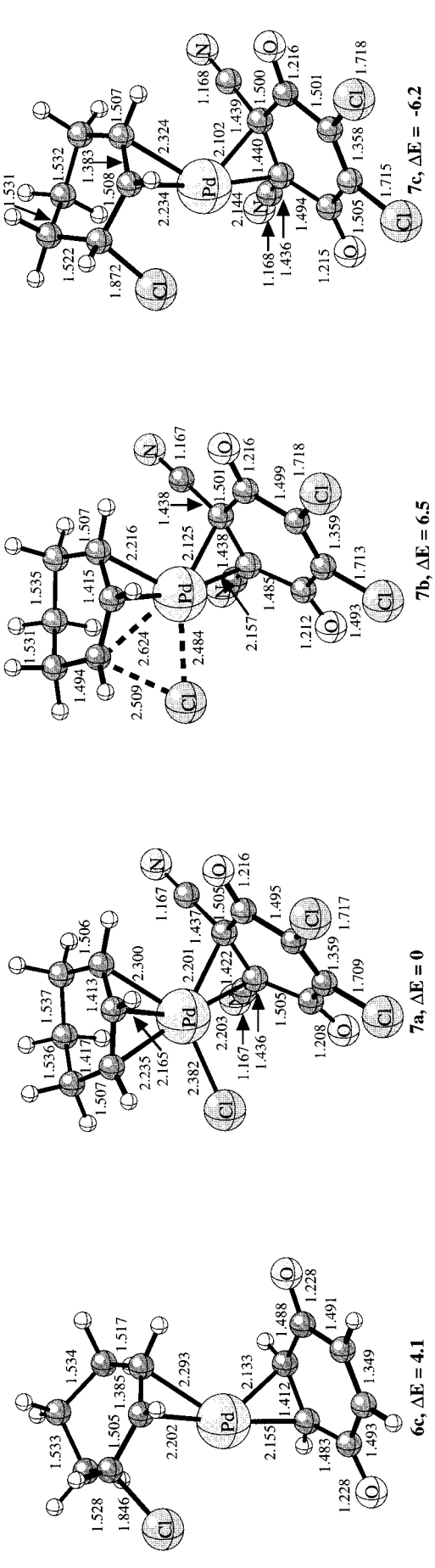

Figure 1. B3PW91/LANL2DZ+P energies and geometries **1**−**7** (energies in kcal/mol, bond lengths in Å). The zero-point vibration corrected energies for **1**−**4** are given in an italic type face.

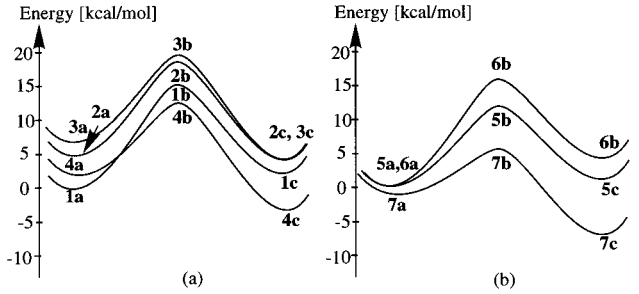

Figure 2. Reaction profiles calculated at the B3PW91/LANL2DZ+P level of theory for (a) acyclic complexes **1**−**4** and (b) cyclic species **5**−**7**. The reaction profiles include the isodesmic energy exchange (eqs 2a and 2b); therefore, the energy values are relative to **1a** (a) and **5a** (b).

Geometry and Stability of the (η^3-Allyl)palladium-Cl(BQ) Complexes. *p*-Benzoquinone may coordinate to (η^3-allyl)palladium-Cl in three different ways, providing **1a**, **1d**, and **1e**. In all three complexes, the C4−C5 bond (see eq 1 for the numeration) of BQ is 0.04 Å longer than the other double bond, indicating an η^2-type coordination to palladium. In **1a** and **1e**, C4 and C5 are in-plane with the allylic terminal carbons (C1 and C3) and the Cl^- atom, while in **1d**, the plane of BQ bisects the coordination plane of palladium. The main difference between the modes of coordination in **1a** and **1e** is that the distance between the noncoordinating carbons of BQ and the allylic terminal carbons is considerable longer in **1a** (*exo* coordination) than in **1e** (*endo* coordination). The stability of the three complexes is rather similar, although the *exo* form (**1a**) is somewhat more stable than its *endo* counterpart (**1e**) and the bisected form (**1d**).

The η^2 coordination of the relatively bulky BQ ligand leads to a considarable steric strain with the Cl^- ligand and with the allylic terminal carbon C3. The Cl−C4-(BQ) distance is 3.17−3.28 Å, which is considerably shorter than the sum of the van der Waals radii of the Cl and C(sp^2) atoms (3.5 Å).[38] This steric interaction displaces the Cl^- ligand toward the C1 of the allyl moiety. The C1−Cl distance in **1a** (3.09 Å) is shorter, by 0.3 Å, than the corresponding distance in (η^3-allyl)-palladium(Cl_2).[39] Displacement of Cl^- by BQ is one of the most important steric factors to facilitate the ligand migration in these complexes.

Since the plane of the BQ ligand is perpendicular to the coordination plane of palladium, C5 (BQ) closely approaches C3 (allyl). In **1a**, the C5−C3 distance (3.35 Å) is shorter than the van der Waals distance between two sp^2 carbon atoms[38] (3.5 Å). The C5−C3 distance in the *endo* form (**1e**) is even shorter (3.07 Å), which explains its lower stability compared to **1a**. In the bisected form (**1d**), the C3−C5 distance (3.58 Å) is longer than in the other two forms; however, in **1d**, another type of steric interaction appears between H4, H5, and the Cl^- ligand. The H4−Cl and H5−Cl distances are 2.94 and 2.83 Å, which are shorter than the sum of the van der Waals radii of the Cl and H atoms (3.0 Å).[38] A

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subtle interplay between the different steric interactions leads to a somewhat lower stability of the bisected form (**1d**) compared to the *exo* form (**1a**). Replacement of H4 and H5 with more bulky groups will further destabilize the bisected form; as a consequence, the bisected forms of tetrasubstituted BQ derivatives do not represent minima on the potential energy surface (vide infra).

The allyl−palladium bonding is strongly asymmetric in all three species. The Pd−C1 bond (2.14−2.16 Å) *trans* to BQ is somewhat longer than the Pd−C1 bond in a (η^3-allyl)palladium(Cl_2) complex (2.13 Å);[39] however, the Pd−C3 (2.2 Å) bond *cis* to BQ is considerable longer than the other two Pd−C bonds. Accordingly, BQ exerts *cis* influence on the allyl−palladium bonding.[40] This *cis* influence has a steric rather than an electronic origin, and it can be explained by the C3 (allyl)−C5 (BQ) interactions. Elongation of the Pd−C3 bond partially relives the steric strain between C3 and C5.

In **1d**, BQ has a local C_s symmetry: C4−C9 and C5−C6 are about equally long (1.49 Å), and the C−O bond lengths are also very similar (1.22 Å). However, the BQ ligand does not possess any local symmetry in **1a** and **1e**, with the C−O bond lengths especially being rather different. The lack of local symmetry is due to the asymmetric coordination of C4 and C5 to palladium. The asymmetric coordination of BQ is clearly reflected by the group charges on C4 and C5 (vide infra) and the different Pd−C bond lengths. For example, in the most stable complex (**1a**), the Pd−C5 bond (2.23 Å) is somewhat shorter than the Pd−C4 bond (2.24 Å).

The Cl^- migration from complexes **1a** and **1d** proceeds via the same TS structure **1b**, while the reaction starting from the *endo* complex **1e** passes TS structure **1f**. In the TSs of Cl^- migration (**1b** and **1f**), the Pd−C1 and Pd−Cl bonds are being broken and the C1−Cl bond is being formed. Elongation of the C1−C2 bond is a consequence of the $sp^2 \rightarrow sp^3$ rehybridization of C1, while formation of an η^2-alkene−Pd bond is indicated by shortening of the C2−C3 bond. An increasing electronic interaction between palladium and BQ is indicated by shortening of the Pd−C4 and Pd−C5 bonds and elongation of the C4−C5 double bond. The activation barrier (15 kcal/mol) to *cis* migration of Cl^- is rather high, so complexes such as **1a** do not undergo internal attack by nucleophiles.[12]

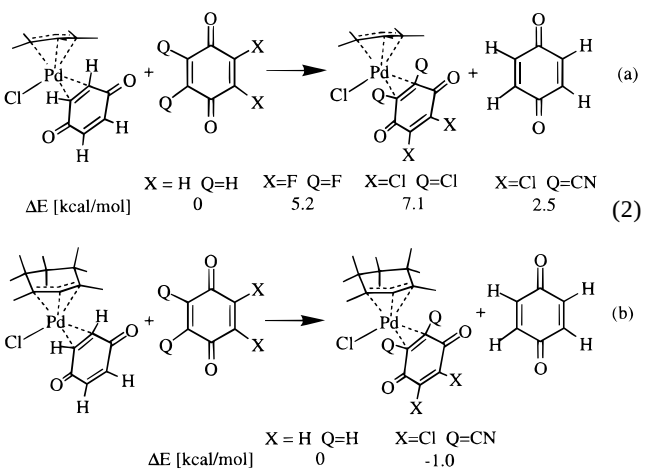
As was mentioned in section 2, characterization of the stationary points was done at the B3PW91/3-21G level of theory. The B3PW91/3-21G and B3PW91/LANL2DZ+P geometries of **1b** are quite similar, and the structure calculated with the small basis set was characterized by one imaginary frequency. The zero-point energy correction was rather small, 0.3 kcal/mol (Figure 1).

The primary product of *cis* migration (**1c**) incorporates η^2-coordinated allyl chloride and η^2-coordinated BQ. The mode of coordination of BQ is the same as in the X-ray structure of the [Pd(0)(bipy)(BQ)] complex recently reported by Milani and co-workers.[41] The coordination of palladium to allyl chloride is considerably weaker than that to BQ, as shown by the Pd−C and C=C bond lengths. The weak Pd−C2 and Pd−C3 bonds in **1c** lead to a facile decomplexation of the olefin formed, which is vital in catalytic transformations in order to maintain the catalytic cycle. There is still a weak Pd−Cl interaction in **1c**, indicating that the reverse process, the oxidative addition of allyl chloride to palladium, is also possible. Kurosawa and coworkers[42] have studied the stereochemistry of the oxidative addition of allylic chlorides to Pd(0). According to these authors, when the solvent interactions does not prevent the Pd−Cl bond formation, the oxidative addition follows a *syn* mechanism, i.e., the Cl atom is transferred from the allylic moiety directly to the palladium atom. Since the oxidative *syn* addition is the reverse of the *cis* migration, the *syn* addition reported by Kurosawa and co-workers[42] proceeds through a TS that is probaly very similar to **1b**.

Effects of Substitution of BQ. The migration aptitude of Cl^- was studied as a function of substituent effects of F (**2**), Cl (**3**), and CN (**4**). The corresponding quinones: fluoranyl (**2**), chloranyl (**3**), and 2,3-dichloro-5,6-dicyanobenzoquinone (DDQ, **4**), are inexpensive, commercially available compounds that can be used as cocatalysts in catalytic transformations.

The substituted BQ derivatives have only two different modes of coordination to palladium: *exo*- (**2a**, **3a**, and **4a**) and *endo*-type (**2d**, **3d**, and **4d**) coordination. The bisected form (cf. **1d**) does not exist because of steric interactions between the Cl^- ligand and the quinone substituents. An increase of the bulkiness of the quinone ligand also increases the stability of the *exo* form in comparison with the *endo* form. In the case of the DDQ ligand, two different *exo* and *endo* forms exist, since DDQ can coordinate through either its Cl^- or its CN-substituted carbons. Coordination by the CN-substituted carbons leads to more stable complexes (3.4 kcal/mol) than coordination by the Cl-substituted ones. The Pd−C bond lengths in **1a**−**4a** are rather similar; however, in the DDQ-coordinated complex (**4a**), the Pd−C1 and Pd−C2 bonds are somewhat weaker and the Pd−C4 and Pd−C5 bonds are somewhat stronger than in the parent, BQ-coordinated complex (**1a**). The variation in the Pd−C1 bond strengths is of great relevance for the migration of Cl^-, since this bond has to be cleaved in the reaction.

The relative stability of the complexes can be calculated by the isodesmic eq 2a. According to this equation,



(40) Appleton, T. G.; Clark, H. C.; Manzer, L. E. *Coord. Chem. Rev.* **1973**, *10*, 335.

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ligand exchange of BQ with substituted BQ derivatives is an endothermic process. In particular, exchange of BQ with chloranyl leads to considerable destabilization (7.1 kcal/mol). The least destabilizing process (2.5 kcal/mol) is exchange of BQ with DDQ, leading to the **4a** form. Coordination of the quinones to palladium is an important prerequisite for the subsequent Cl^- migration. Destabilizing interactions in the case of chloranyl (**3a**) and fluoranyl (**2a**) coordination decrease the ability of these quinone ligands to effectively induce ligand migration. The relative stability of **2a**−**4a** is influenced by both steric and electronic effects. The steric interactions are particularly strong between the substituent of C4 and the Cl^- ligand, but they also occur between the substituent of C5 and C3. The electronic interactions arise from the substituent effects on the π-orbital energy of the quinone (vide infra).

The geometry of the TS structures is similar to that of **1b**; however, as one goes from **1b** to **4b**, the C1−Cl distance progressively increases and the Pd−Cl distance decreases, suggesting an "earlier" TS for **2b**−**4b** than for the parent, BQ-coordinated complex **1b**. The activation barrier to Cl^- migration decreases in the same order. Exchange of the BQ ligand of **1a** with the DDQ ligand (**4a**) leads to a considerable decrease in the activation energy (5.1 kcal/mol). The reaction profiles for various quinone ligands on palladium (Figure 2a) clearly indicate that the DDQ-coordinated complex (**4a**) performs the most facile Cl^- migration. The TS structures were characterized by a single imaginary frequency at the B3PW91/3-21G level of theory. The zero-point vibration corrections decrease the activation barrier by 0.3−0.4 kcal/mol.

In the reaction products (**2c**, **3c**, and **4c**) the olefin−palladium bonding is even weaker than in **1c**, suggesting that the decomplexation of allyl chloride is easier in the case of the substituted quinones than in the case of the BQ-containing complex. Although the Cl^- migration is an exothermic process for **2**−**4**, the DDQ-mediated ligand migration (**4a** → **4c**) is considerably more exothermic (−5.4 kcal/mol) than the other two reactions (**2a**,**3a** → **2c**,**3c**).

Effects of Substitution of the Allyl Moiety. Variation of the activation energy as a function of the alkyl substitution of the allyl moiety is studied for [η^3-(1,2,3)-cyclohexenyl]palladium complexes, which are of considerable practical importance.[12−15,43] The cyclohexyl ring may have chair (**5a**) or boat (**6a**) conformation. The boat conformer is more stable by 0.1 kcal/mol than the chair form. In both forms, the Pd−C1 bond is longer than in the acyclic complex **1a**, indicating a relatively weak allyl−Pd interaction. The Pd−C(allyl) bonds in the chair conformer of [η^3-(1,2,3)-cyclohexenyl]palladium complexes are usually longer than in the boat forms, which is also the case for **5a** and **6a**.[23,39,44] Exchange of the BQ ligand of **5a** with a DDQ ligand (**7a**) leads to a further elongation of the Pd−C1 bond. Notably, the Pd−C1 bond in **7a** (2.24 Å) is 0.1 Å longer than the corresponding Pd−C1 bond in (η^3-allyl)palladium(Cl_2).[39]

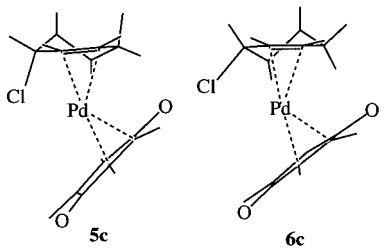

Figure 3. Side view of the B3PW91/LANL2DZ+P structures of **5c** and **6c**.

The isodesmic eq 2b shows that exchange of the BQ ligand of **6a** with a DDQ ligand is an exothermic process, suggesting that coordination of DDQ to a [η^3-(1,2,3)-cyclohexenyl]palladium complex is even more feasible than coordination of BQ.

The Cl^- migration proceeds through TS structures **5b**−**7b**. For the chair forms (**5b** and **7b**), the C1−Cl distances are considerable longer than in the acyclic forms, indicating the presence of an "earlier" TS. Surprisingly, the activation barrier is considerably (by 3.9 kcal/mol) higher for the boat conformer (**6**) than for the chair conformer (**5**). The activation barrier in the DDQ-coordinated complex (**7**) is only 6.5 kcal/mol. Accordingly, the Cl, CN substitution of BQ and alkyl substitution of the allyl moiety simultaneously decrease the activation barrier for Cl^- migration. The reaction profiles in Figure 2b clearly indicate that the *cis* migration of Cl^- has the lowest activation barrier in the DDQ-coordinated [η^3-(1,2,3)-cyclohexenyl]palladium species **7**.

The BQ-activated process is an endothermic reaction, since **5c** and **6c** are less stable by 4−6 kcal/mol than the corresponding [η^3-(1,2,3)-cyclohexenyl]palladium species (**5a** and **6a**), while the DDQ-mediated process is exothermic (−6 kcal/mol). The reverse reaction (**7c** → **7a**) is still possible for the DDQ-coordinated complex; however, its activation energy (12.7 kcal/mol) is considerably higher than that of the *cis* migration (6.5 kcal/mol).

Comparison of the side view of **5c** and **6c** (Figure 3) reveals that ligand migration in the chair (**5a**) and boat forms (**6a**) of [η^3-(1,2,3)-cyclohexenyl]palladium provides two different half-chair conformers of cyclohexene. Because of the different conformation of the chlorocyclohexene moiety in **5c** and **6c**, the Pd−Cl distance is significantly longer, by 0.2 Å, in **6c** (3.0 Å) than in **5c** (2.79 Å). Accordingly, the Cl^- migration path is substantially longer in the **6a** → **6c** process than in case of the **5a** → **5c** process, which also explains the higher activation barrier for the boat form (**6**) than for the chair form (**5**).

Analysis of the NBO Charges. Inspection of the data in Table 1 reveals that the BQ ligands generate an asymmetric electron distribution in the allylic moiety of **1a**−**7a**. The positive charge is larger by 0.02−0.04 electrons on the C1 carbon atom *trans* to the quinone ligands than on the other terminal position (C3). The electron distribution on the quinone ligands is also asymmetric: the negative charge on C5 is larger by 0.04−0.07 electrons than the negative charge on the other coordinating carbon C4. The electron distribution between the allyl and quinone ligands shows a clear pattern: the group charge on the allyl moiety is always

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Table 1. NBO Group Charges[a]

	q(C1H$_2$)[b]	q(C3H$_2$)[b]	q(C4Q)[c]	q(C5Q)[c]	q(allyl)[d]	q(qu)[e]	q(Cl)	q(Pd)
1a	0.081	0.042	−0.059	−0.092	0.135	−0.142	−0.547	0.552
1b	0.236	0.046	−0.119	−0.117	0.194	−0.303	−0.399	0.507
1c	0.130	0.004	−0.149	−0.110	0.050	−0.360	−0.099	0.406
2a	0.086	0.048	−0.036	−0.074	0.155	−0.139	−0.550	0.532
2b	0.248	0.065	−0.093	−0.104	0.233	−0.315	−0.402	0.485
2c	0.137	0.025	−0.128	−0.096	0.088	−0.384	−0.088	0.386
3a	0.100	0.061	−0.091	−0.136	0.180	−0.197	−0.540	0.558
3b	0.248	0.076	−0.156	−0.171	0.249	−0.378	−0.397	0.525
3c	0.136	0.030	−0.190	−0.166	0.095	−0.444	−0.084	0.433
4a	0.127	0.095	−0.189	−0.278	0.243	−0.312	−0.511	0.580
4b	0.263	0.103	−0.254	−0.267	0.301	−0.476	−0.378	0.554
4c	0.148	0.056	−0.291	−0.267	0.145	−0.550	−0.068	0.473
5a	0.079	0.060	−0.069	−0.105	0.207	−0.189	−0.566	0.547
5b	0.243	0.060	−0.131	−0.130	0.304	−0.350	−0.459	0.506
5c	0.108	0.015	−0.155	−0.123	0.105	−0.367	−0.115	0.407
6a	0.075	0.053	−0.064	−0.104	0.196	−0.180	−0.571	0.556
6b	0.230	0.048	−0.131	−0.129	0.267	−0.348	−0.423	0.503
6c	0.091	0.007	−0.148	−0.115	0.075	−0.369	−0.102	0.397
7a	0.126	0.112	−0.219	−0.261	0.352	−0.397	−0.527	0.572
7b	0.270	0.109	−0.279	−0.293	0.444	−0.551	−0.447	0.552
7c	0.120	0.057	−0.307	−0.288	0.214	−0.603	−0.090	0.479

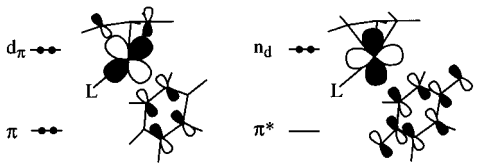
[a] In electrons. [b] Group charges on the allylic terminal positions. In case of **5**−**7** q(C1H) and q(C3H). [c] Group charges on the quinone carbons coordinated to palladium (Q = H, F, Cl, and CN). [d] Group charges on the allylic moiety. In case of **5**−**7**, on the η^3-(1,2,3)-cyclohexenyl moiety. [e] Group charges on the quinone ligand.

positive, and that on the quinone is always negative. As one goes from the BQ-coordinated complex (**1a**) to the DDQ-coordinated one (**4a**), the charge polarization between the allyl and quinone ligands increases progressively: the positive charge on the allyl ligand increases from 0.14 (**1a**) to 0.24 (**4a**) electrons, while the negative charge on the quinone ligand increases from −0.14 (**1a**) to −0.31 (**4a**) electrons.

The charge polarization between the allyl and quinone moieties is considerably larger in the TS structures (**1b**−**7b**) than in the corresponding allylpalladium complexes (**1a**−**7a**). It is also more pronounced in the [η^3-(1,2,3)-cyclohexenyl]palladium complexes (**5**−**7**) than in the corresponding unsubstituted acyclic complexes (**1** and **4**). There is a clear correlation between the electron distribution of **1a**−**7a** and the activation energy of the Cl$^-$ migration. Substantial charge polarization between the allyl and quinone leads to a low activation barrier. Although all quinone ligands are net electron acceptors, DDQ is a considerably more efficient acceptor than BQ. The low activation barrier to the Cl$^-$ migration in **4** and **7** can be ascribed to the large electron-accepting capacity of the DDQ ligand compared to that of BQ.

The quinone ligands bear considerably larger negative charges in the products of the Cl$^-$ migration (**1c**−**7c**) than in the precursors (**1a**−**7a**). In **4c** and **7c**, the DDQ ligands bear a negative charge of over −0.5 electrons. On the other hand, as one goes from **1a**−**7a** to **1c**−**7c**, the positive charge decreases only by 0.11−0.15 electrons on the palladium. This is surprising in view of the fact that the internal Cl$^-$ migration is formally considered as a reductive elimination involving Pd(II) → Pd(0) interconversion. However, the NBO analysis shows that the electron density does not build up on palladium during the Cl$^-$ migration, but, rather, it is transferred directly to the quinone, indicating that the internal nucleophilic attack and the reoxidation of palladium take place simultaneously.

Chart 1

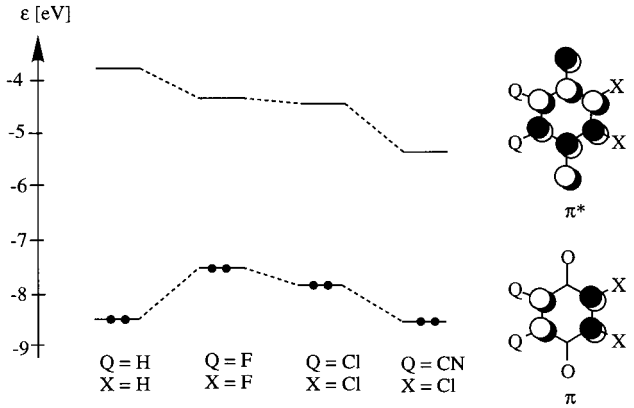


The electron acceptor capacity of the quinone ligand appears to be one of the most important factors determining the ligand migration aptitude in (η^3-allyl)-palladium complexes. A qualitative description of the most important MO interactions between the quinone and the (η^3-allyl)palladium-Cl fragment is provided in Chart 1. There are two high-lying π orbitals of BQ (π and π^*) that are properly oriented to interact with the d orbitals of the metal. A four-electron destabilizing interaction occurs between the filled palladium−allyl bonding orbital (d_π) and the filled π orbital of BQ. This destabilizing interaction is compensated by back-donation from a lone-pair d orbital (n_d) of palladium to the π^* orbital of BQ.

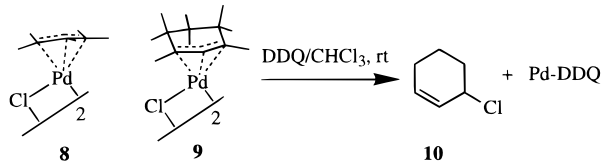
Substitution of BQ by electron-withdrawing substituents leads to a lowering of the π^* energy level, diminishing (Chart 2, B3PW91/LANL2DZ+P data) the energy gap between π^* and n_d, which leads to enhanced back-donation, and thereby an increased transfer of electron density to the quinone ligand. In the case of fluoranyl and chloranyl, the F and Cl substitution raises the π orbital energy, increasing the interactions between the filled π and d_π levels, destabilizing the complex (cf. eq 2a). This effect is absent in the case of the DDQ ligand, and the slight destabilization on ligand exchange with BQ is due to steric interactions between the (C4)−CN group and the Cl ligand of palladium.

In the chair form of the [η^3-(1,2,3)-cyclohexenyl]-palladium complex, the Pd−C(allyl) bonding is elongated, destabilizing the d_π level, which leads to a weaker four-electron interaction with the π orbital of quinone and, therefore, an exothermic ligand exchange of BQ with DDQ (cf. eq 2b). Weakening of the Pd−C1 bond

Chart 2



Scheme 1



also lowers the activation energy, since this bond has to be cleaved during the ligand migration.

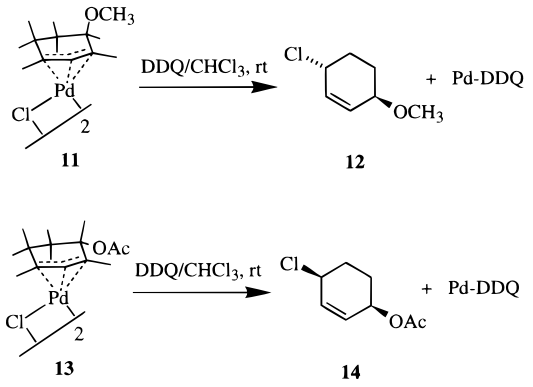
4. Experimental Verification of the Theoretical Results

Theoretical predictions on the outstanding activation ability of DDQ in ligand migration reactions are also tested by experimental studies. It is well known that BQ is not able to activate Cl^- migration when it is reacted with (η^3-allyl)palladium complexes.[12,14] Chloroform solution of **8** and **9** can also be kept unchanged for several days in the presence of BQ, fluoranyl, and chloranyl. However, in complete agreement with the theoretical predictions, rapid formation of 3-chlorocyclohexene (**10**) could be observed when **9** and DDQ were mixed in chloroform (Scheme 1). The reaction was complete in 1 min at room temperature, yielding **10** quantitatively.

Studies on the Stereoselectivity of the Reaction. Since the ligand migration reaction is highly stereoselective (eq 1), the *cis* migration mechanism can be ascertained by investigating the stereochemistry of the reaction. Therefore, the experimental studies were extended to stereodefined (η^3-allyl)palladium complexes **11** and **13**, Scheme 2.

Complex **11** can be obtained by stereospecific reaction of cyclohexadiene with palladium chloride in methanol.[12,45] Since the methoxy group of **11** is *trans* to palladium, the *cis* migration is expected to provide a *trans*-disubstituted product. And, indeed, when this complex was reacted with DDQ in chloroform at room temperature, *trans*-4-methoxy-1-chloro-2-cyclohexene[46] (**12**) was formed. Monitoring the reaction by ^{1}H NMR spectroscopy revealed that the ligand migration takes place with a very high stereoselectivity without formation of *cis*-4-methoxy-1-chloro-2-cyclohexene[46] or other side products. The regioselectivity of the reaction was also very high, which is expected according to previous

Scheme 2



experimental and theoretical studies on nucleophilic attack on **11**.[12,22,39] Since **11** can easily be prepared from cyclohexadiene, its reaction with DDQ can also be employed as an alternative method for stereoselective synthesis of **12**, which is otherwise prepared from cyclohexene in four steps.[46] Conditions for the reaction on a preparative scale are given in the experimental part.

Finally, another check was made on the stereochemistry using complex **13**. The preparation and characterization of this *cis*-substituted complex was reported recently.[44] Reaction of **13** with DDQ in chloroform provided *cis*-1-acetoxy-4-chloro-2-cyclohexene (**14**).[14] The stereoselectivity was again very high, since the *trans* isomer[47] did not form at all. The facts that the *trans*-substituted complex **11** gave *trans* product **12** stereoselectively, and that the *cis*-substituted complex **13** provided the *cis* product **14**, clearly prove the *cis* mechanism of the DDQ-mediated Cl^- migration.

5. Relevance of This Study in Allylpalladium Chemistry

Since (unsubstituted) BQ is usually employed as cocatalyst in synthetically useful palladium(II)-catalyzed reactions proceeding via allylpalladium complexes, this theoretical study can also help organic chemists to design new catalytic transformations. A deeper understanding of the mechanism of the stereoselective ligand migration would facilitate the selection of the appropriate nucleophiles, quinone derivatives, and substrates in these reactions.

Nucleophilic Attack by Ligands with Low Migration Aptitude. The above study shows that the application of electronegative substituents on BQ dramatically increases the ligand migration aptitude of the Cl^- nucleophile coordinated to palladium. The low migration aptitude of Cl^- arises from the strong Pd−Cl bonding,[21,23] since this bond has to be cleaved in the reaction. However, the low migration aptitude can also arise from the low nucleophilicity of the ligand. Benzoquinone derivatives with electron-withdrawing substituents such as DDQ and chloranyl generate considerable positive charge on the allyl moiety, increasing its reactivity toward nucleophiles. Therefore, these quinone derivatives are also expected to induce migration of weakly nucleophilic ligands. However, employ-

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ment of bulky ligands with low nucleophilicity should be avoided because of the steric strain occurring between the ligand and BQ derivatives.

Choice of Substituted BQ Auxiliaries. Electron-withdrawing substituents lower the π^* energy level of BQ, improving the ability of these BQ derivatives to effectively induce ligand migration. However, substituents with low-lying lone-pair orbitals, such as Cl, raise the energy of the filled π level, which thermodynamically destabilizes the (η^3-allyl)palladium−quinone complex, whence BQ derivatives with such substituents have a relatively weak coordination affinity to palladium (cf. eq 2a).

Bulky substituents on BQ also destabilize the allylpalladium complexes. The steric interactions are particularly strong between the substituent at C4 of BQ and the Cl^- or other ligands on palladium. Substituents at C5 of BQ can sterically interact with C3 of the allyl moiety. On the other hand, bulky substituents on BQ selectively stabilize the *exo*-type coordination in comparison to the *endo*-type coordination. The CN group on BQ represents a substituent that is particularly favorable for induction of ligand migration in (η^3-allyl)-palladium complexes: (a) it is a moderately bulky substituent; (b) it does not possess lone-pair electrons on the C atom attached to BQ; and (c) it can effectively decrease the π orbital energy level of BQ (Chart 2).

Substituents on the Allyl Moiety. Since the ligand migration process involves Pd−C1 bond cleavage, substituents that weaken the allyl−palladium bonding, such as alkyl cycloalkyl groups,[39] are expected to facilitate the migration process. This effect is particularly important in the chair conformer of [η^3-(1,2,3)-cyclohexenyl]palladium complexes (e.g., **7a**), which undergo *cis* Cl^- migration much faster than their unsubstituted acyclic counterparts (e.g., **4a**). The final conformation of the product also influences the activation energy. The hindered rotation in cyclic systems can lead to product conformations, in which the "migration path" is relatively long, such as in the boat form of [η^3-(1,2,3)-cyclohexenyl]palladium complexes (**6**). The stability of **5a** and **6a** is the same within 0.1 kcal/mol, suggesting that these two forms are about equally populated at room temperature. However, the boat and chair conformers of the η^3-(1,2,3)-cyclohexenyl ring can be selectively stabilized by, for example, employing OMe[48] or COOMe[49] substituents at the 5-position. According to the above results, the activation barrier for *cis* migration is predicted to be higher in a complex that is biased to boat conformation than in one which is constrained to chair conformation. Consequently, the conformation of the complex will determine the rate of the internal nucleophilic attack, providing a powerful tool for controlling the stereoselectivity of the catalytic transformation.

6. Conclusions

This study discusses the BQ-induced Cl^- migration in (η^3-allyl)palladium complexes as a function of the substituents on the BQ ligand and on the allyl moiety. Benzoquinone and its derivatives coordinate to palladium in an η^2 fashion. The bulky BQ ligand pushes the Cl^- toward the allyl moiety, facilitating the ligand migration. Several types of coordinations, such as *endo*, *exo*, and bisected types, are possible, providing allylpalladium complexes of similar stability.

The effects of substituents on BQ can be summarized as follows: (1) electron-withdrawing substituents decrease the activation energy of the ligand migration; (2) substituents with high-lying lone pairs destabilize the (η^3-allyl)palladium−quinone complexes; and (3) bulky substituents sterically interact with the Cl^- ligand and the allyl moiety.

Alkyl substituents on the allyl moiety weaken the allyl−palladium bonding and, therefore, decrease the activation barrier of the ligand migration. The product conformation also influences the activation energy. Ligand migration requires a longer "migration path" in the boat conformer of [η^3-(1,2,3)-cyclohexenyl]palladium complex than in the chair conformer, which results in a higher activation barrier in the case of the boat form.

The most favorable substituent effects for the Cl^- migration are encountered in the DDQ-coordinated complex with an η^3-(1,2,3)-cyclohexenyl moiety (**7**). The feasibility of the Cl^- migration in such a complex has also been verified by an experimental study (Scheme 1), which also demonstrated the very high stereoselectivity of the ligand migration process (Scheme 2). The experimental studies have also provided the first examples of ligand-induced Cl^- migration in (η^3-allyl)-palladium complexes.

Experimental Section

^{1}H NMR Experiments. A 2.5-μmol portion of the appropriate complex (**8**, **11**, or **13**) was mixed with 5 μmol of BQ, chloranyl, fluoranyl, and DDQ in 0.7 mL of $CDCl_3$ at room temperature, and the reaction was followed by ^{1}H NMR spectroscopy. In the case of addition of BQ, chloranyl, and fluoranyl, the (η^3-allyl)palladium complexes remained unchanged for several days. Addition of DDQ to **9**, **11**, and **13** resulted in formation of allyl chloride derivatives **10**, **12**, and **14**, respectively. The products were identified by comparing their ^{1}H NMR spectra with those of authentic samples.[14,46,50]

Preparation of 12. Complex **11**[12,45] (500 mg, 1 mmol) was dissolved in CH_2Cl_2 (150 mL) at 0 °C, followed by addition of DDQ (610 mg, 2.7 mmol). After stirring at 0 °C for 2 h, the reaction mixture was extracted by water, 0.1 m NaOH solution, and, once again, water. The colorless organic phase was dried by $MgSO_4$, evaporated, and purified by chromatography using pentane−ether (9:1) eluent, yielding 270 mg (92%) of **12**.[46]

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Supporting Information Available: Calculated B3PW91/LANL2DZ+P geometries (18 pages). See any current masthead page for ordering information.

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