# Mechanism of Nucleophilic Attack on 1- and 2-Bromo($\pi$-allyl)palladium Complexes[1]

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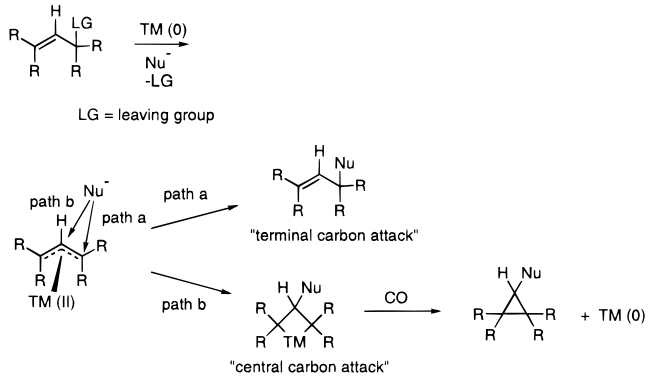
**Abstract:** It has been demonstrated that attack of sodium phenoxide nucleophile on the $\pi$-allyl Pd complexes generated from both 2,3- (**1**) and 1,3-dibromo-1-propene (**15**) is strongly regioselective for the central carbon, producing 2-bromo- and 3-bromo-3-phenoxy-1-palladacyclobutane, respectively. Then, via different mechanisms, both intermediates converge to produce 1,2-diphenoxy-2-propene (**2a**) as the final product in good yield. Through the use of extensive deuterium labeling studies, a multistep mechanism for the formation of **2a** from **15** has been delineated. Phenol derivatives substituted with electron-donating groups attack the central carbon of the $\pi$-allyl Pd complexes derived from both **1** and **15**. Electron-withdrawing groups on phenol shift regioselectivity for attack on the terminal carbon, kinetically. The regioselectivity of phenoxide attack is sharply inverted to the terminal carbon for both **1** and **15** when the ligand is changed from the $\pi$-acceptor ligand triphenylphosphine to tetramethylethylenediamine. The use of catechol, now possessing two nucleophilic sites, has extended this methodology to the production of a substituted 1,4-dioxane product that represents a new ring annulation approach for the production of such compounds.

## Introduction

That nucleophiles attack the central carbon of transition metal (TM) $\pi$-allyl complexes has been known for over 20 years,[2] although this event is rare when compared to attack at the termini of such species. Most additions of highly stabilized nucleophiles, such as malonate-type anions, occur by attack at the terminal carbon of a TM $\pi$-allyl complex (Scheme 1, path a).[3] Nonstabilized nucleophiles, such as Grignard-based reagents, attack the electron-deficient metal center, and the group is transferred subsequently to the terminal carbon of the $\pi$-allyl metal complex by reductive elimination via the corresponding $\sigma$-complex.[3] In cases where attack does occur at the central carbon of the $\pi$-allyl moiety, the mechanism is less well delineated, but addition is known to involve metallacyclobutane formation (Scheme 1, path b).[2]

TM $\pi$-allyl complexes that have demonstrated the ability to support nucleophilic attack at the central carbon include complexes of molybdenum,[2,4] tungsten,[2,4] platinum,[5−7] palladium,[8−11] manganese,[12] zirconium,[13] titanium,[13] iridium,[14,15] and rhodium.[14,16] Anions that have served as active nucleophiles

**Scheme 1**

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(3) For general discussion regarding Pd-catalyzed substitution of allylic substrates and leads to original references, see: Tsuji, J. *Palladium Reagents and Catalysis. Innovations in Organic Synthesis*; Wiley: Chichester, 1995; pp 61−124.

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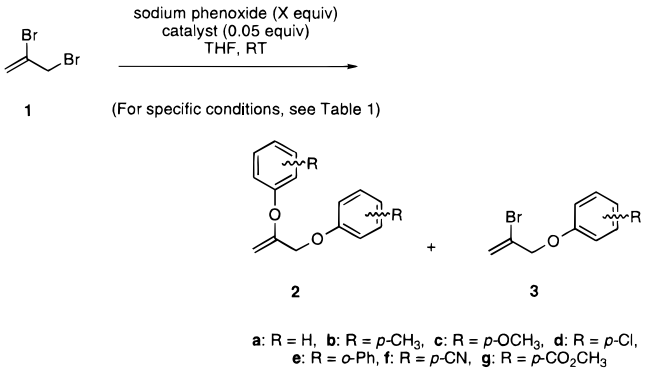
**Scheme 2**




in these additions include malonate-type anions,[8,10] less stabilized enolate-type anions,[6,9,15] and nonstabilized anions, such as simple alkyl (e.g., alkyllithium or Grignard reagents)[2,13] and hydride reagents (e.g., $NaBH_4$ or Red-Al).[2] The most commonly observed fate of the metallacyclobutane is cyclopropane formation, which occurs by reductive elimination accompanied by release of the TM complex.[8,9,11,15] The metallacyclobutane itself is stable and can be isolated and characterized.[9c] Cyclopropane formation can be promoted by running the reaction under carbon monoxide.[9]

Recently, an interesting study by Bäckvall and co-workers has demonstrated that, in the case of Pd catalysis, the ligands on the metal play a significant role in determining the regioselectivity in the attack of sodium dimethyl methylmalonate on the Pd $\pi$-allyl complex derived from 2,3-dichloro-1-propene.[10] With a variety of phosphine ligands, attack occurred predominantly or exclusively at the termini of the complex, whereas nitrogen-based ligands 2,2′-bipyridine and tetramethylethylenediamine (TMEDA) led to attack exclusively on the central carbon. We are currently developing a series of tandem Pd-catalyzed substitution reactions involving the corresponding dibromide substrate **1**, and we found these results to be relevant to our own interests.

## Results and Discussion

Treatment of **1** with 1.0 equiv of sodium phenoxide in the presence of catalytic $(PPh_3)_4Pd$ failed to provide any of the allylic substitution product (**3**) (see Scheme 2 and Table 1, entry 1). Instead, **2a** was isolated in 95% yield based on phenoxide, and the remaining dibromide was recovered almost quantitatively. When the reaction was performed with 2.0 equiv or more of sodium phenoxide (5% $(PPh_3)_4Pd$ in THF, at room temperature, hereafter called standard conditions; Table 1, entries 2 and 3), all of **1** was consumed, and **2a** was isolated in 75 and 78% yields, respectively.

Altering the concentration of the reaction with respect to **1** (Table 1, entries 4 and 5) or increasing the number of equivalents of sodium phenoxide relative to **1** (Table 1, entries 1, 2, and 3) did not alter the regioselectivity of this reaction. However, changing the ligand from triphenylphosphine (TPP) to TMEDA (Table 1, entry 6) sharply inverted the apparent selectivity from central to terminal carbon attack exclusively. These results are in stark contrast to all previously published reports on this subject with Pd catalysis, where regioselectivity of attack with a variety of carbon-based nucleophiles is the exact opposite for both ligand systems.[8−10]

This reaction also proceeded cleanly with a variety of phenoxide-based nucleophiles that are comparatively electron-poor or -rich (Table 1, entries 7−13). Electron-rich phenoxides (entries 7 and 8) gave exclusively the product of central carbon attack (i.e., **2**). Electron-poor phenoxides appear to have a tendency to give the terminal carbon attack product (i.e., **3**) kinetically (entries 11 and 12). The progress of these reactions was followed by $^1H$ NMR spectroscopy, and a significant amount of **3f** was produced at the beginning of the reaction which slowly converts into **2f** over time. This terminal attack product can re-ionize due to the increased stability of the resultant leaving group to provide **2f** as the thermodynamic product over time. However, the ester derivative (entry 12) appears to provide only **2g** both kinetically and thermodynamically. Phenoxy product **3a** has been shown not to re-ionize when resubmitted to standard reaction conditions; thus, **2a** is both the kinetic and thermodynamic product with sodium phenoxide nucleophile (vide infra). Consistent with the results of Bäckvall and co-workers,[10] treatment of **1** with the carbon-based nucleophile dimethyl methylmalonate using standard conditions provided terminal attack product **4a** exclusively in high yield (see Experimental Section). This substitution, which is complete in less than 10 s, was proven to be Pd-catalyzed in control experiments without Pd. This is also true of all additions using phenol-based nucleophiles.

**Mechanism for the Formation of 2 from 1.** The formation of **2** from **1** can be explained using a rationale proposed by Bäckvall et al. (Scheme 3).[10] It is also possible that **1** could be converted to allene in the presence of Pd, and it is, in fact, allene that is being converted to **2**. Similar results have been obtained with allene and lithium bromide nucleophile in the presence of Pd(II).[17] However, Bäckvall's group's earlier study indicated that such a mechanism was inconsistent with the data that they obtained using sodium dimethyl methylmalonate nucleophile.[10] Further, the exclusive formation of **4** when this nucleophile was used under identical reaction conditions as phenoxide in this study (vide supra) also casts doubt on the formation of allene on route to **2**.

**Tethered Nucleophiles—The Synthesis of Ring-Annulated Products.** If the nucleophilic atoms were incorporated into the same molecule, the possibility existed to prepare cyclic products. Such an approach would represent a conceptually new method of constructing six-membered ring heterocycles (Scheme 4). Treatment of **1** with the disodium salt of catechol in the presence of $(PPh_3)_4Pd$ resulted in a highly complex mixture of products, none of which resembled **5**. However, when the monoanion of catechol was generated with NaH and this nucleophile was allowed to react with **1** in the presence of $(PPh_3)_4Pd$ and anhydrous potassium carbonate, **5** was produced cleanly as the sole product.

**Effects of Altering 2,3-Dibromo-1-propene Structure.** To study the effects of steric crowding on the Pd $\pi$-allyl species generated from these reactions, a number of derivatives of **1** were prepared (Scheme 5). When **6** was treated with standard reaction conditions, **7** and **8** were produced in nearly quantitative recovery. Both products clearly originate from initial attack of phenoxide at the central carbon of the Pd $\pi$-allyl complex. In this case, steric crowding does not seem to alter the approach of phenoxide to the initially formed $\pi$-allyl intermediate. However, this steric effect significantly hinders the approach of the second phenoxide to the monophenoxy-substituted Pd $\pi$-allyl intermediate (see Scheme 3). Compound **8** presumably arises from $\beta$-hydride elimination from the corresponding $\sigma$-bound Pd cationic intermediate, which is in equilibrium with the $\pi$-allyl complex. Interestingly, when the two alkyl groups were tied back into a ring (i.e., **9** or **12**), the regioselectivity of

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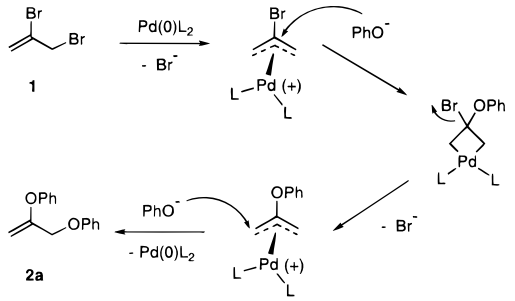
**Table 1.** Attack of Phenoxide Derivatives on the π-Allyl Pd Complex Derived from **1**

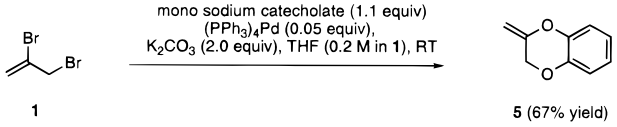
| entry | nucleophile (amount, equiv) | catalyst[a] | concn of **1** (mol/L) | ratio of **2**:**3** (product number) | combined yield (%)[b] |
|---|---|---|---|---|---|
| 1 | sodium phenoxide (1.0) | $(PPh_3)_4Pd$ | 0.2 | 1:0 (**2a**:**3a**) | 47 (95)[c] |
| 2 | sodium phenoxide (2.0) | $(PPh_3)_4Pd$ | 0.2 | 1:0 (**2a**:**3a**) | 75 |
| 3 | sodium phenoxide (3.0) | $(PPh_3)_4Pd$ | 0.2 | 1:0 (**2a**:**3a**) | 78 |
| 4 | sodium phenoxide (3.0) | $(PPh_3)_4Pd$ | 0.5 | 1:0 (**2a**:**3a**) | 70 |
| 5 | sodium phenoxide (3.0) | $(PPh_3)_4Pd$ | 0.05 | 1:0 (**2a**:**3a**) | 82 |
| 6 | sodium phenoxide (3.0) | Pd-TMEDA[d] | 0.2 | 0:1 (**2a**:**3a**) | 69 |
| 7 | sodium 4-methylphenoxide (3.0) | $(PPh_3)_4Pd$ | 0.2 | 1:0 (**2b**:**3b**) | 79 |
| 8 | sodium 4-methoxyphenoxide (3.0) | $(PPh_3)_4Pd$ | 0.2 | 1:0 (**2c**:**3c**) | 71 |
| 9 | sodium 4-chlorophenoxide (3.0) | $(PPh_3)_4Pd$ | 0.2 | 1:0 (**2d**:**3d**) | 72 |
| 10 | sodium 3-phenylphenoxide (3.0) | $(PPh_3)_4Pd$ | 0.2 | 1:0 (**2e**:**3e**) | 76 |
| 11 | sodium 4-cyanophenoxide (3.0) | $(PPh_3)_4Pd$ | 0.2 | 1:0 (**2f**:**3f**)[e] | 95 |
| 12 | sodium 4-(methylcarboxy)phenoxide (3.0) | $(PPh_3)_4Pd$ | 0.2 | 1:0 (**2g**:**3g**) | 95 |

[a] Reactions were performed as follows: phenol was added to a suspension of NaH in THF at room temperature. After the mixture was stirred for 15 min, catalyst was added, followed by **1** via syringe. [b] Based on isolated product following silica gel chromatography. [c] Based on recovered **1**. [d] Pd-TMEDA catalyst system was generated by adding 1 or 2 equiv of TMEDA to a solution of $Pd_2(DBA)_3-CHCl_3$ in THF. This was then added to a solution of sodium phenoxide in THF, followed by 2,3-dibromopropene (**1**), and the reaction followed as usual. [e] Ratio is thermodynamic and is determined upon workup after reacting for 4 h at room temperature. Compound **3f** is the kinetic product which slowly converts to **2f** over time.

**Scheme 3**




**Scheme 4**




the initial nucleophilic attack was reversed completely to that observed with **1** or **6**.

**Role of the C2 Halide in Regioselectivity of Initial Nucleophilic Attack.** It was of interest to know if the halide at the central position of the π-allyl complex derived from **1** was involved in promoting nucleophilic attack at this position. A halide here would increase the amount of positive charge that could be supported at the central carbon of the π-allyl Pd complex via π-donation. This effect has been demonstrated recently with a 1-methoxy-π-allyl Pd complex, where stabilized nucleophiles added to the more sterically hindered end of the π-allyl bearing the methoxy group.[18] In the absence of the halide at C2, attack might be expected to be directed to the terminal end of the complex in the present study.

Treatment of 1,3-dibromo-1-propene (1.5:1 trans:cis) (**15**) with standard conditions led to the formation of **2a** in addition to some of the allylic substitution product **16a** (Scheme 6). Other phenoxide-based nucleophiles were reacted with **15** to see if the electronic nature of the nucleophile altered the regioselectivity of attack with this substrate (see Table 2, entries 7−10). Attack at the central position is favored by electron-rich phenoxides and disfavored by electron-poor ones, relative to sodium phenoxide itself. When strongly electron-withdrawing groups are used (entry 9), for the first time in this study, no product of central carbon attack is observed.

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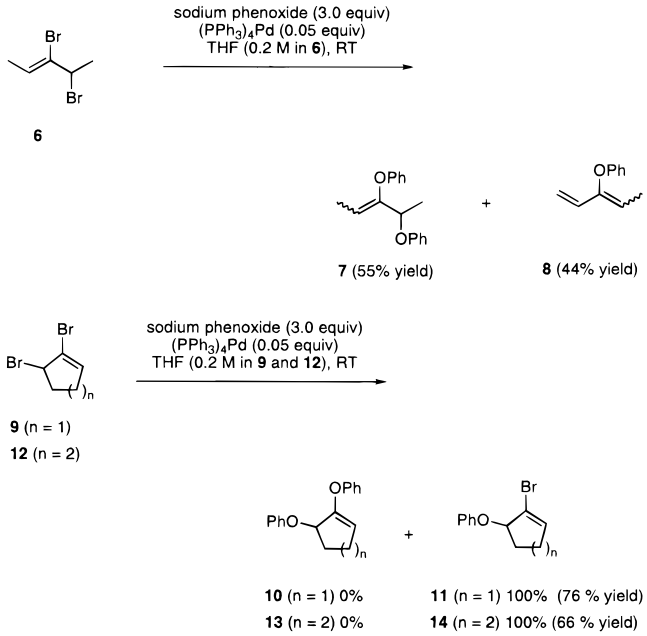
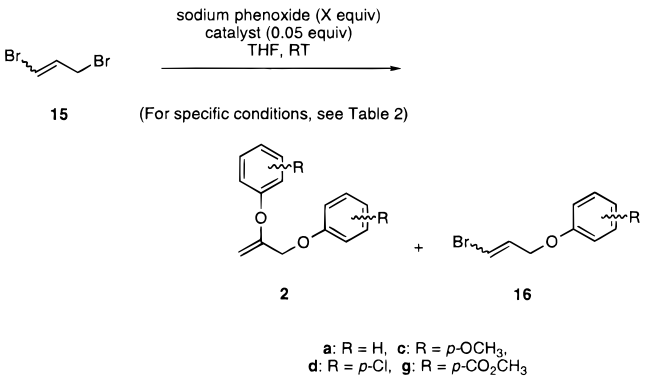
**Scheme 5**




**Scheme 6**




In contrast to the results with **1**, regioselectivity of nucleophilic attack on the complex formed from **15** with the same catalyst was noticeably concentration-dependent (see Table 2, entries 1, 2, and 3). At 0.2 M, there was a slight preference shown for the terminal attack product **16a**, whereas at 0.1 and 0.05 M, a preference for **2a** now was observed. In at least two runs at 0.05 M, **2a** was the only product produced, but this result

**Table 2.** Attack of Phenoxide Derivatives on the p-Allyl Pd Complex Derived from **15**

| entry | nucleophile (amount, equiv) | catalyst[a] | concn of **15** (mol/L) | ratio of **2**:**16** (product number) | combined yield (%)[b] |
|---|---|---|---|---|---|
| 1 | sodium phenoxide (3.0) | $(PPh_3)_4Pd$ | 0.2 | 1:1.2 (**2a**:**16a**) | 80 |
| 2 | sodium phenoxide (3.0) | $(PPh_3)_4Pd$ | 0.1 | 1.9:1 (**2a**:**16a**) | 80 |
| 3 | sodium phenoxide (3.0) | $(PPh_3)_4Pd$ | 0.05 | 2.0:1 (**2a**:**16a**) | 75 |
| 4 | sodium phenoxide (2.0) | $(PPh_3)_4Pd$ | 0.1 | 2.0:1 (**2a**:**16a**) | 70 |
| 5 | sodium phenoxide (4.0) | $(PPh_3)_4Pd$ | 0.1 | 2.0:1 (**2a**:**16a**) | 82 |
| 6 | sodium phenoxide (3.0) | Pd-TMEDA[c] | 0.1 | 0:1 (**2a**:**16a**) | 70 |
| 7 | sodium 4-methoxyphenoxide (3.0) | $(PPh_3)_4Pd$ | 0.1 | 4.1:1 (**2c**:**16c**) | 56 |
| 8 | sodium 4-chlorophenoxide (3.0) | $(PPh_3)_4Pd$ | 0.1 | 1:3.8 (**2d**:**16d**) | 87 |
| 9 | sodium 4-(methylcarboxy)phenoxide (3.0) | $(PPh_3)_4Pd$ | 0.1 | 0:1 (**2g**:**16g**) | 95 |

[a] Reactions were performed as follows: phenol was added to a suspension of NaH in THF at room temperature. After the mixture was stirred for 15 min, catalyst was added, followed by **1** via syringe. [b] Based on isolated product following silica gel chromatography. [c] Pd-TMEDA catalyst system was generated by adding 1 or 2 equiv of TMEDA to a solution of $Pd_2(DBA)_3-CHCl_3$ in THF. This was then added to a solution of sodium phenoxide in THF, followed by 2,3-dibromopropene (**15**), and the reaction followed as usual.

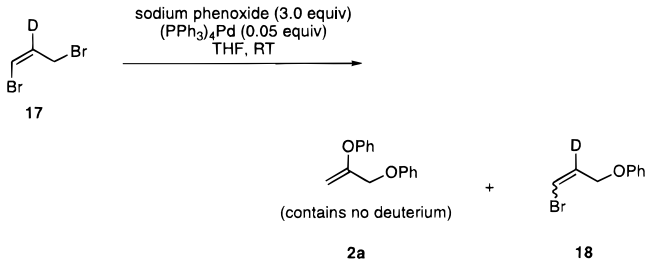
was not consistently reproducible. For all three of these studies, the amount of phenoxide ion was held constant at 3.0 equiv relative to **15**. Two more experiments were conducted where the concentration of the reaction was held at 0.1 M in **15** and the amount of phenoxide was altered to 2.0 and 4.0 equiv (see Table 2, entries 4 and 5). Relative to the result obtained with 3.0 equiv, altering the amount of nucleophile does not alter significantly the product distribution.

As with **1**, attack of phenoxide nucleophile with **15** was dramatically affected by the nature of the ligand (see Table 2, entry 6). Whereas the $\pi$-allyl complex with TPP-ligated Pd gave mainly central carbon attack, switching to TMEDA ligand once again shifted regioselectivity exclusively to terminal carbon attack. With dimethyl methylmalonate nucleophile, both ligands gave terminal carbon attack with **15** (see Experimental Section, compound **4b**), whereas Bäckvall's 2,3-dichloro-1-propene substrate had exclusively central carbon attack when using a Pd-TMEDA catalyst.

**Mechanism for the Formation of 2 from 15.** The presence of **16a** in the product mixture of reactions utilizing **15** raised the possibility that **2a** was being formed from **16a**, and terminal attack may well be favored kinetically. The phenoxy group could actually undergo a sequence of additions and re-ionizations before ultimately forming **2** via disproportionation. If this was occurring, the analytical methods used to monitor reactions in this study might be too crude to spot it. It is also possible that both **3a** and **16a** are being formed from **1** and **15**, respectively, and a common intermediate derived from these allylic substitution products goes on to provide **2**. Although **3a** was not isolated in any reaction performed using standard conditions with **1** and phenoxide, it is possible that **3a** is the kinetic product. To probe this, **3a** and **16a** were reacted under standard conditions, but neither was converted to **2a**. Therefore, it is unlikely that **3a** or **16a** is serving as an intermediate in the formation of **2a** from **1** or **15**, respectively. Attack at C1 of the initially formed $\pi$-allyl Pd complex terminates the reaction for phenoxide itself and electron-rich phenoxide derivatives because they are too basic to re-ionize. This is indicative that two very different mechanisms are operating with **1** and **15**.

With substrate **1**, there is no obvious reason to dispute the mechanism proposed by Bäckvall et al. (Scheme 3). The mechanism involved in the conversion of **15** to **2a** is clearly much more complex and must account for no less than six discrete bond-breaking and bond-making events. One aspect that needed to be addressed was the removal of the C2 hydrogen and the incorporation of it, or a different hydrogen, at either C1 or C3 in the final product. To probe this, a number of experiments were carried out using deuterium-labeled starting materials. Compound **17** was prepared (geometrically pure) and treated with the standard reaction conditions to follow the fate

**Scheme 7**




of the C2 deuterium atom (Scheme 7). Within the levels of error of NMR and mass spectroscopy, there was little, if any, deuterium in the diphenoxy product (see Figure 1). Assuming that no special deuterium isotope effects were operating, this result indicated that the C2 hydrogen was removed in a form that prohibited it from being re-incorporated readily back into that same molecule or another one. A noteworthy observation in this study is the fact that **18** is produced as a mixture of geometric isomers, thus proving the involvement of Pd catalysis in the allylic substitution.

Given the reaction conditions, perhaps the new hydrogen was coming from phenol through ortho metalation by Pd, accompanied by transfer of the hydrogen in some form to the propene fragment. To probe this, perdeuterated phenol (i.e., phenol-$d_6$) was used, and the reaction was carried out under otherwise normal conditions with **15** (Scheme 8). Equal amounts of **19a** and **19b** were produced, indicating that the label had, in fact, been transferred from phenol to the propene fragment. We are confident that **19c** is present from the HRMS that displays a very prominent parent ion peak for the formula $C_{15}H_4D_{10}O_2$, as well as one for $C_{15}H_3D_{11}O_2$ that corresponds to **19a** and **19b**. This can also been seen by inspection of the $^{13}C$ NMR spectra shown in Figure 1.

The $^1H$ and $^{13}C$ NMR spectra of this mixture also revealed that no hydrogen was incorporated into the phenol ring(s) of the products. If metalation of the ring were taking place, then a proton from the aqueous workup would have quenched the metalated site. Therefore, the label was not coming from the ring of phenol, but rather from the $-OD$ position. To confirm this, the $-OD$ of perdeuterated phenol was replaced by a proton to provide $C_6D_5OH$. The reaction with this phenol derivative and **15** was then repeated, and this time no label was transferred to the propene fragment, and **19c** and **20** were the only products isolated.

It remained unclear how the phenolic $-OH$ was being transferred to the product when it had presumably been removed from the reaction as hydrogen gas following deprotonation with NaH prior to the addition of Pd(0) and **15**. For the standard reaction, addition of phenol to a suspension of NaH in THF

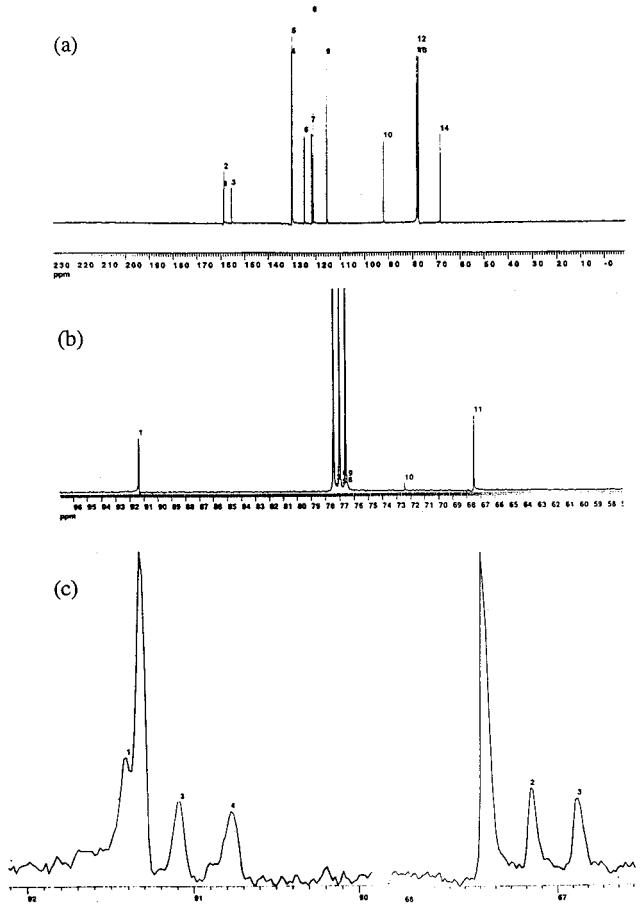
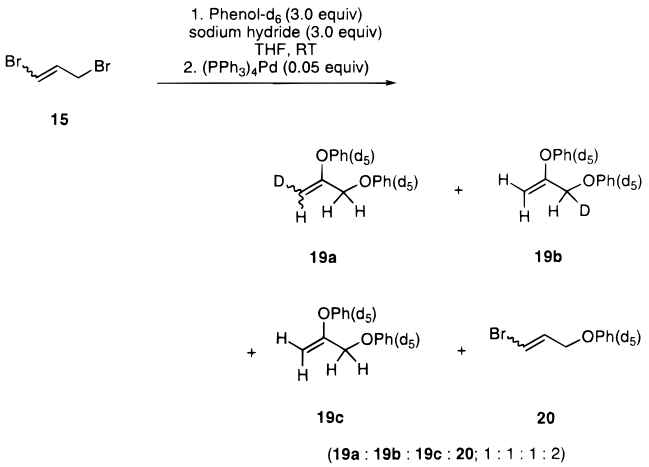


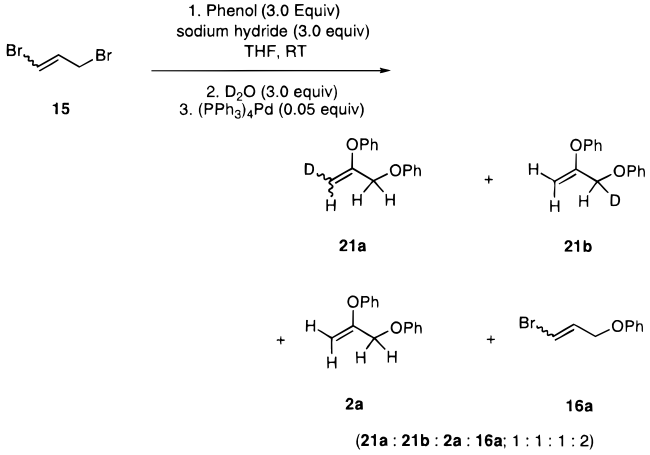

**Figure 1.** $^{13}C$ NMR spectra of products from schemes 2, 7, and 8. (a) Full $^{13}C$ spectrum of **2a** derived from the reaction outlined in Scheme 2. (b) Partial $^{13}C$ spectrum of **2a** derived from the reaction outlined in Scheme 7. The two peaks indicated are those arising from carbons 1 and 3, and it is clear that there are no resonances from a carbon bound to a deuterium, other than that of the $CDCl_3$ solvent between the two peaks. (c) The two sets of enlarged peaks demonstrated here are those of the mixture of 1,2-diphenoxy-1-propene products arising from the reaction detailed in Scheme 8. Note that the areas under both deuterated carbon signals are approximately equal (spectra are on the same scale) and that both signals are shifted about 0.3 ppm upfield of those arising from the diphenoxy compounds not possessing a deuterium at that same site.

**Scheme 8**




was highly exothermic and was accompanied by vigorous gas evolution, leading to a fully homogeneous reaction mixture. Therefore, it seemed unlikely that $H_2$ or HD was the H source

**Scheme 9**



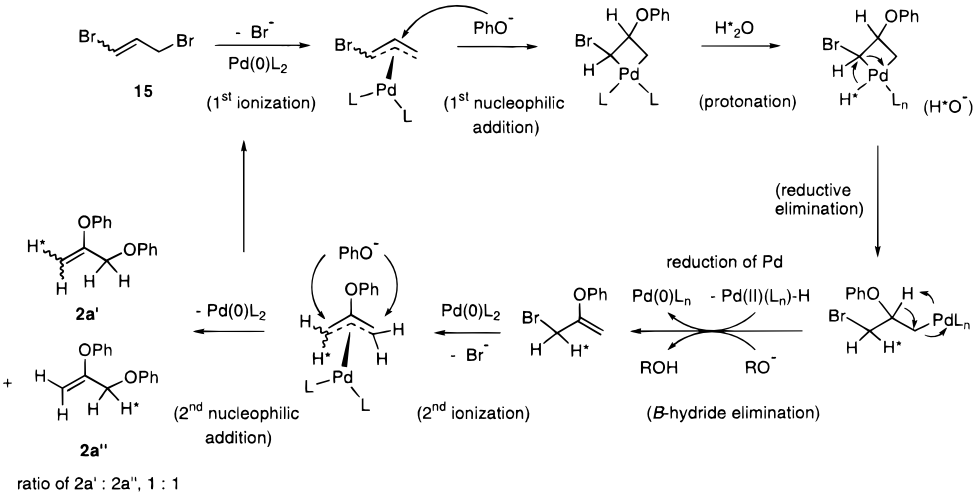

in the transformation leading to **2a** from **15**. Further, in the experiments with perdeuterated phenol, it was clear from the accurate mass spectroscopy analysis of the product that **19c** was also present in roughly equal amounts with **19a** and **19b**. The formation of **19c** involved the transfer of hydrogen and not deuterium. This indicates that phenol was not the only source of hydrogen in this reaction. Reviewing the results, the most likely source of hydrogen in this reaction was water, which would be formed during deprotonation from the NaOH present in NaH. To this end, regular phenol was deprotonated with NaH, and 3 equiv of $D_2O$ was added prior to the addition of Pd(0) and **15** (Scheme 9). The product mixture was found to contain the same 1,2-diphenoxy-1-propene products as when perdeuterated phenol was used; that is, deuterium was incorporated into the propene fragment (**21a** and **21b**). Therefore, based on these studies, it appears likely that water, or at least RO−H, is the actual source of the H in these studies, which is presumably transferred as a proton.

The mechanism leading to the formation of **2** from **15** must account for the following experimental data: (1) the ionization of both bromides and their replacement with two phenoxide ion molecules; (2) the removal of the C2 hydrogen from the starting material and its replacement with a different hydrogen that can come from water; and (3) the symmetrical distribution of deuterium at C1 and C3 in the runs with perdeuterated phenol and $D_2O$. With these issues in mind, we propose the mechanism outlined in Scheme 10. There is precedent for what appears to be a protonation−reductive elimination−$\beta$-hydride elimination sequence with tungsten metallacyclobutane, using aqueous $DBF_4$ that opened to give 3-deuterio-1-propene and tungsten hydride.[2a] Although these acidic conditions seem more conducive to metal protonation than those in the present study, it would seem unlikely that the H is being delivered as a radical or hydride given the reaction conditions. Further, the reaction is catalytic, indicating that protonation of some anionic species at the end of the reaction upon workup does not occur, and protonation is part of the catalytic cycle.

## Summary

The reaction of **1** with 2.0 equivalents or more of sodium phenoxide in the presence of $(PPh_3)_4Pd$ in THF solvent results in attack of the nucleophile primarily at the central carbon of the initially formed $\pi$-allyl Pd complex, leading to the formation of **2a**. This is the complete opposite of the regioselectivity seen when sodium dimethyl methylmalonate nucleophile is used

**Scheme 10**




under identical conditions, where attack is now terminal.[19] Steric crowding on acyclic derivatives of **1** does not alter regioselectivity away from central carbon attack with phenoxide nucleophile. The use of tethered nucleophilic oxygens in catechol has led to the production of a substituted dioxane product that represents a conceptually new method for the construction of such a compound. In stark contrast to the ligand effects demonstrated by a number of groups where nitrogen-based ligands promoted central carbon attack with malonate-type nucleophiles, switching from the $\pi$-acceptor ligand TPP to TMEDA (a non-$\pi$-acceptor) alters the regioselectivity of phenoxide attack to the terminal position exclusively.

The formation of **2** from **15** in this study (with phosphine ligands on Pd) was a conceptually interesting discovery. From the very first reactive intermediate formed with **1**, symmetry issues guided the development of a mechanism for the production of **2** from **1**. The reactive intermediates derived from **15**, regardless of the mechanism employed, must be mainly unsymmetrical. This made rationalizing the equal distribution of deuterium label in **19a** and **19b** a challenge. The need for the involvement of water in this reaction was also an interesting discovery that is, to our knowledge, unprecedented in metallacyclobutane chemistry.

It is clear that the sum of forces involved that direct phenoxide addition to the central carbon in **1** are much stronger than those directing regioselectivity with **15**. Terminal attack product **16** was observed in varying amounts in almost every experiment conducted involving **15**. As we observed with **1**, switching the ligand from TPP to TMEDA reversed regioselectivity from central to terminal carbon attack exclusively. Electron-rich 4-methoxyphenoxide gave reproducibly more central carbon attack product than did phenoxide itself, which was higher than that of 4-chlorophenoxide, which showed a pronounced preference for terminal attack with **15**. Strongly electron-withdrawing 4-(methylcarboxy)phenoxide gave only terminal attack with **15**.

All of the above data concerning regioselectivity of nucleophilic attack on the initially formed $\pi$-allyl Pd complex clearly indicate that subtle changes in the nucleophile can bring about large changes in regioselectivity. We are now investigating further the differences between malonate and phenoxide nucleophiles in conjunction with the $\pi$-allyl Pd complexes generated in this study. Explanations given to explain differences in regioselectivity with $\pi$-allyl metal complexes are being considered.[20] Also, we are initiating our own computational project that pays particular attention to the nucleophile, as well as the allyl fragment and the ligands on Pd.

(19) See results in this study, and also see ref 10.

## Experimental Section

All reactions were carried out under a positive atmosphere of dry argon. All reaction vessels were first equipped with a stir bar and then flame-dried. Tetrahydrofuran (THF) solvent was distilled from sodium benzophenone immediately prior to use. Melting points are uncorrected. NMR spectra were recorded in $CDCl_3$ at 300 MHz for proton spectra and at 75 MHz for carbon spectra. Chemical shifts are listed relative to $CHCl_3$ ($\delta$ 7.24 for $^1$H NMR and $\delta$ 77.00 for $^{13}$C NMR). $^{13}$C NMR spectra obtained using the APT pulse sequence (indicated by APT in parentheses prior to the $\delta$ symbol) display positive signals for quaternary carbons and carbons that are attached to an even number of protons. Signals for carbons that are attached to an odd number of protons are negative.

**1,2-Diphenoxy-2-propene (2a).** The following procedure is the general one that was used for all Pd-catalyzed substitution reactions with phenoxide-based nucleophiles. Into a 10-mL test tube were added THF (1 mL) and NaH (3.0 equiv, 36.2 mg, 60 mg of 60% dispersion in mineral oil, 1.50 mmol), and this suspension was stirred at room temperature. To this, phenol (3.0 equiv, 141 mg, 1.50 mmol) was added slowly to control $H_2$ gas evolution. To this homogeneous solution was added 29.0 mg of $(PPh_3)_4Pd$ (0.05 equiv, 0.025 mmol), followed by 1.5 mL of THF to rinse all components off the walls of the flask and into solution. 2,3-Dibromo-1-propene (**1**) (100 mg, 0.50 mmol) was then added neat by syringe, and the mixture was stirred for 16 h. The suspension was then diluted with 40 mL of ether and loaded into a separatory funnel, along with 5 mL of saturated ammonium chloride. After shaking, the layers were separated, and the aqueous layer was extracted twice with ether. The organic layers were then combined and dried over anhydrous $MgSO_4$. Following solvent removal in vacuo, the residue was loaded on top of a prepacked silica gel column and flashed (straight pentane, $R_f = 0.2$), providing 88.3 mg (78.1% yield) of **2a** as a clear oil. $^1$H NMR ($CDCl_3$, 75 MHz): $\delta$ 7.38−7.25 (m, 4H), 7.17−7.04 (m, 3H), 7.02−6.93 (m, 3H) 4.63 (s, 2H), 4.59 (d, $J$ = 2.20 Hz, 1H), 4.24 (d, $J$ = 2.20 Hz, 1H). $^{13}$C NMR ($CDCl_3$, 300 MHz): $\delta$ 158.43, 158.19, 155.02, 129.64, 129.43, 124.30, 121.23, 120.65, 115.01, 91.31, 67.46. IR (neat): 3094, 3064, 3042, 1651 cm$^{-1}$. HRMS: calcd for $C_{15}H_{14}O_2$ [M]$^+$ 226.0994, found 226.0995.

Unless indicated otherwise, all reactions below were performed using the general procedure on a scale of 50−100 mg of **1** or **15**. Yields are reported in Tables 1 and 2 in the Results section.

**1,2 Di-(4-methylphenoxy)-2-propene (2b).** The product was isolated as white crystals, mp = 61.5−63.0 °C. $^1$H NMR ($CDCl_3$, 300

(20) (a) Bäckvall, J.-E.; Björkman, E. E.; Pettersson, L.; Siegbahn, P. *J. Am. Chem. Soc.* **1984**, *106*, 4369−4373. (b) See ref 6.

MHz): δ 7.19−7.07 (m, 4H), 6.99 (d, $J$ = 8.1 Hz, 2H), 6.91 (d, $J$ = 8.8 Hz, 2H), 4.62 (s, 2H), 4.55 (d, $J$ = 2.2 Hz, 1H), 4.21 (d, $J$ = 2.2 Hz, 1H), 2.34 (s, 3H), 2.31 (s, 3H). $^{13}$C NMR ($CDCl_3$, 75 MHz): δ 158.69, 156.38, 152.65, 133.85, 130.42, 130.11, 129.87, 120.61, 114.91, 90.27, 67.75, 20.74, 20.45. IR (neat): 3030 cm$^{-1}$. Anal. Calcd for $C_{17}H_{18}O_2$: C, 80.28; H, 7.13. Found: C, 80.22; H, 7.17.

**1,2-Di-(4-methoxyphenoxy)-2-propene (2c).** The product was isolated as white crystals, mp = 70.6−72.2 °C. $^1$H NMR ($CDCl_3$, 300 MHz): δ 7.03−6.80 (m, 8H), 4.58 (s, 2H), 4.47 (d, $J$ = 1.5 Hz, 1H), 4.10 (d, $J$ = 1.5 Hz, 1H), 3.78 (s, 3H), 3.76 (s, 3H). $^{13}$C NMR ($CDCl_3$, 75 MHz): δ 159.32, 156.40, 154.20, 152.60, 148.22, 121.99, 116.16, 114.64, 114.57, 89.50, 68.54, 55.64, 55.62. IR (neat): 3072 cm$^{-1}$. Anal. Calcd for $C_{17}H_{18}O_4$: C, 71.31; H, 6.34. Found: C, 71.19; H, 6.39.

**1,2-Di-(4-chlorophenoxy)-2-propene (2d).** The product solidifies upon sitting in a freezer. $^1$H NMR ($CDCl_3$, 300 MHz): δ 7.34−7.19 (m, 4H), 6.99 (d, $J$ = 8.8 Hz, 2H), 6.89 (d, $J$ = 8.8 Hz, 2H), 4.58 (s, 3H), 4.24 (d, $J$ = 2.2 Hz, 1H). $^{13}$C NMR ($CDCl_3$, 75 MHz): δ 157.70, 156.91, 153.42, 129.75, 129.64, 129.36, 126.26, 122.00, 116.29, 92.03, 67.73. IR (neat): 3096, 3069 cm$^{-1}$. HRMS: calcd for $C_{15}H_{12}Cl_2O_2$ $[M]^+$ 294.0216, found 294.0218.

**1,2 Di-(3-phenylphenoxy)-2-propene (2e).** The product was isolated as a clear oil. $^1$H NMR ($CDCl_3$, 300 MHz): δ 7.42−6.74 (m, 18H), 4.52 (s, 2H), 4.47 (s, 1H) 4.17 (s, 1H); $^{13}$C NMR ($CDCl_3$, 75 MHz): δ 158.82, 158.08, 155.49, 143.03, 142.78, 140.31, 129.96, 129.75, 128.80, 128.74, 127.61, 127.43, 127.15, 127.07, 126.75, 123.07, 120.24, 119.32, 119.29, 114.11, 113.77, 91.99, 67.67. IR (neat): 3059, 3033 cm$^{-1}$. HRMS calcd for $C_{27}H_{22}O_2$ $[M]^+$ 378.1621, found 378.1612.

**1,2 Di-(4-cyanophenoxy)-2-propene (2f).** The product was isolated as white crystals, mp = 85−86 °C. $^1$H NMR ($CDCl_3$, 300 MHz): δ 7.62 (d, $J$ = 8.67 Hz, 2H), 7.58 (d, $J$ = 8.64 Hz, 2H), 7.15 (d, $J$ = 8.67 Hz, 2H), 6.98 (d, $J$ = 8.69 Hz, 2H), 4.86 (s, 1H), 4.65 (s, 2H), 4.55 (s, 1H). $^{13}$C NMR ($CDCl_3$, 75 MHz): δ 161.26, 158.84, 155.23, 134.14, 134.01, 120.14, 118.85, 118.39, 115.49, 107.61, 104.86, 96.77, 67.17. IR (neat): 3019, 2255, 2228 cm$^{-1}$.

**1,2 Di-(4-methylcarboxyphenoxy)-2-propene (2g).** The product was isolated as white crystals, mp = 92−93 °C. $^1$H NMR ($CDCl_3$, 300 MHz): δ 8.02 (d, $J$ = 8.64 Hz, 2H), 7.98 (d, $J$ = 8.74 Hz, 2H), 7.10 (d, $J$ = 8.43 Hz, 2H), 6.96 (d, $J$ = 8.73 Hz, 2H), 4.78 (s, 1H), 4.65 (s, 2H), 4.47 (s, 1H), 3.87 (s, 3H), 3.85 (s, 3H). $^{13}$C NMR ($CDCl_3$, 75 MHz): δ 166.43, 166.15, 161.72, 159.01, 156.06, 131.45, 131.42, 125.76, 123.11, 119.27, 114.28, 94.88, 66.97, 51.85, 51.66. IR (neat): 1715.9 cm$^{-1}$.

**2-Bromo-1-phenoxy-2-propene (3a).** The product was isolated as clear oil. $^1$H NMR ($CDCl_3$, 300 MHz): δ 7.28 (t, $J$ = 8.1 Hz, 2H), 6.97 (t, $J$ = 7.4 Hz, 1H), 6.91 (d, $J$ = 8.8 Hz, 2H), 5.98 (d, $J$ = 1.5 Hz, 1H), 5.66 (d, $J$ = 1.5 Hz, 1H), 4.63 (s, 2H). $^{13}$C NMR ($CDCl_3$, 75 MHz): δ 157.77, 129.51, 127.15, 121.57, 117.63, 114.93, 71.62. IR (neat): 3042 cm$^{-1}$; Anal. Calcd for $C_9H_9OBr$: C, 50.73; H, 4.26. Found: C, 50.88; H, 4.27.

**1-(4-Cyanophenoxy)-2-bromo-2-propene (3f).** The product was isolated as a yellow oil. $^1$H NMR ($CDCl_3$, 300 MHz): δ 7.60 (d, $J$ = 8.76 Hz, 2H), 6.97 (d, $J$ = 8.75 Hz, 2H), 5.97 (s, 1H), 5.71 (s, 1H), 4.69 (s, 2H). $^{13}$C NMR ($CDCl_3$, 75 MHz): δ 160.91, 134.26, 125.63, 118.93, 118.62, 115.64, 111.02, 71.63. IR (neat): 3020, 2228 cm$^{-1}$.

**Dimethyl 4-Bromo-2,2-dicarboxy-4-pentene (4a).** $^1$H NMR ($CDCl_3$, 300 MHz): δ 5.65 (s, 1H), 5.58 (d, $J$ = 1.5 Hz, 1H), 3.74 (s, 6H), 3.15 (s, 2H), 1.49 (s, 3H). $^{13}$C NMR ($CDCl_3$, 75 MHz) (APT): δ 171.69 (+), 127.22 (+), 121.89 (+), 53.05 (+), 52.78 (−), 46.11 (+), 19.37 (−). IR (neat): 3001, 1736 cm$^{-1}$. HRMS calcd for $C_9H_{13}O_4Br$ $[(^{79}Br)M + 1]^+$ 265.0075, found 265.0070.

**Dimethyl 5-Bromo-2,2-dicarboxy-4-pentene (4b)** (mixture of cis and trans isomers). $^1$H NMR ($CDCl_3$, 300 MHz): δ 6.31 (dt, $J$ = 6.6, 1.5 Hz, 1H), 6.13−6.04 (m, 3H), 3.73 (s, 12H), 2.79 (dd, $J$ = 7.4, 1.5 Hz, 2H), 2.59 (d, $J$ = 7.4 Hz, 2H), 1.44 (s, 3H), 1.41 (s, 3H). $^{13}$C NMR ($CDCl_3$, 75 MHz) (APT): δ 171.9 (+), 171.8 (+), 132.1 (−) (two coincident), 129.3 (−) (two coincident), 53.3 (+), 53.1 (+), 52.5 (−) (two coincident), 39.1 (+), 35.9 (+), 20.0 (−), 19.9 (−). IR (neat): 2999, 1734 cm$^{-1}$. Anal. Calcd for $C_9H_{13}O_4Br$: C, 40.78; H, 4.94. Found: C, 40.55; H, 5.00.

**Bicyclic Dioxane (5).** $^1$H NMR ($CDCl_3$, 300 MHz): δ 6.94−6.88 (m, 4H), 4.74 (d, $J$ = 1.5 Hz, 1H), 4.49 (s, 2H), 4.34 (s, 1H). $^{13}$C NMR ($CDCl_3$, 75 MHz) (APT): δ 150.15 (+), 143.75 (+), 142.69 (+), 122.28 (−), 122.15 (−), 117.26 (−), 116.48 (−), 91.26 (+), 64.65 (+). IR (neat): 2923 cm$^{-1}$. Anal. Calcd for $C_9H_8O_2$: C, 72.96; H, 5.44. Found: C, 72.82; H, 5.64.

**Pd-Catalyzed Substitution Reaction with 4,5-Dibromo-2-pentene (6) and Sodium Phenoxide (7 and 8). 2,3-Diphenoxy-3-Pentene (7), Major Isomer.** $^1$H NMR ($CDCl_3$, 300 MHz): δ 7.50 (m, 4H), 7.18 (m, 6H), 5.75 (q, $J$ = 6.6 Hz, 1H), 5.03 (q, $J$ = 5.9 Hz, 1H), 1.91 (t, $J$ = 6.6 Hz, 3H), 1.76 (t, $J$ = 5.9 Hz, 3H). $^{13}$C NMR: δ 157.85, 156.99, 150.55, 129.32, 121.58, 121.03, 120.11, 116.06, 115.64, 111.59, 73.43, 19.55, 10.80. IR (neat): 3063, 3029, 1594 cm$^{-1}$. HRMS: calcd for $C_{17}H_{18}O_2$ 254.13074, found 254.13165.

**Minor Isomer.** $^1$H NMR ($CDCl_3$, 300 MHz): δ 7.50 (m, 4H), 7.18 (m, 6H), 5.42 (q, $J$ = 6.0 Hz, 1H), 4.95 (q, $J$ = 6.0 Hz, 1H), 1.76 (m, 6H). $^{13}$C NMR ($CDCl_3$, 75 MHz): δ 157.93, 156.36, 154.38, 129.46, 129.35, 123.23, 121.11, 116.14, 115.53, 104.32, 70.85, 29.69, 19.13.

**3-Phenoxy-1,3-pentadiene (8), Major Isomer Only.** $^1$H NMR ($CDCl_3$, 300 MHz): δ 7.49 (t, $J$ = 8.8 Hz, 2H), 7.17 (d, $J$ = 8.8 Hz, 3H), 6.48 (dd, $J$ = 16.9, 11.0 Hz, 1H), 5.66 (q, $J$ = 7.4 Hz, 1H), 5.42 (d, $J$ = 16.9 Hz, 1H), 5.21 (d, $J$ = 11.0 Hz, 1H), 1.85 (d, $J$ = 7.4 Hz, 3H). $^{13}$C NMR ($CDCl_3$, 75 MHz): δ 157.43, 149.71, 131.72, 129.46, 121.20, 117.17, 114.83, 113.75, 11.22. IR (neat): 3079, 3059, 3040 cm$^{-1}$. HRMS: calcd for $C_{11}H_{12}O$ 160.08886, found 160.08879.

**2-Bromo-1-phenoxycyclopent-2-ene (11).** $^1$H NMR ($CDCl_3$, 300 MHz): δ 7.53 (t, $J$ = 8.1 Hz, 2H), 7.19 (d, $J$ = 8.1 Hz, 3H), 6.47 (s, 1H), 5.40 (t, $J$ = 4.4 Hz, 1H), 2.83−2.58 (m, 3H), 2.31 (m, 1H). $^{13}$C NMR ($CDCl_3$, 75 MHz): δ 158.06, 136.62, 129.48, 121.16, 116.11, 115.96, 85.15, 30.74, 29.99. IR (neat): 3071 cm$^{-1}$. Anal. Calcd for $C_{11}H_{11}BrO$: C, 55.25; H, 4.64. Found: C, 55.37; H, 4.74.

**2-Bromo-1-phenoxycyclohex-2-ene (14).** $^1$H NMR ($CDCl_3$, 300 MHz): δ 7.30 (t, $J$ = 8.1 Hz, 2H), 6.99 (d, $J$ = 8.1 Hz, 3H), 6.39 (m, 1H), 4.76 (s, 1H), 2.27−1.65 (m, 6H). $^{13}$C NMR ($CDCl_3$, 75 MHz): δ 158.04, 134.63, 129.48, 121.47, 121.13, 116.69, 76.39, 29.08, 27.70, 16.64. IR (neat): 3061, 3038 cm$^{-1}$. HRMS calcd for $C_{12}H_{14}BrO$ $[(^{79}Br)M+1]^+$ 253.02282, found 253.02345. HRMS calcd for $C_{12}H_{13}BrO$ $[(^{81}Br)M]^+$ 254.01299, found 254.01985. Anal. Calcd for $C_{12}H_{13}BrO$: C, 56.94; H, 5.18. Found: C, 57.06; H, 5.35.

**Pd-Catalyzed Substitution Reaction with 1,3-Dibromo-1-propene (15) and Sodium Phenoxide (Products 2a and 16a). Inseparable Mixture of Cis and Trans Isomers of 16a.** $^1$H NMR ($CDCl_3$, 300 MHz): δ 7.32 (m, 4H), 7.00−6.87 (m, 6H), 6.45−6.37 (m, 4H), 4.71 (d, $J$ = 4.8 Hz, 2H), 4.43 (d, $J$ = 4.2 Hz, 2H). $^{13}$C NMR ($CDCl_3$, 75 MHz) (APT): δ 158.17 (+), 158.09 (+), 132.63 (−), 131.25 (−), 129.48 (−), 129.40 (−), 121.26 (−), 121.10 (−), 114.93 (−), 114.69 (−), 67.44 (+), 66.12 (+). IR (neat): 3064, 3039 cm$^{-1}$. Anal. Calcd for $C_9H_9OBr$: C, 50.73; H, 4.26. Found: C, 51.05; H, 4.41.

**Pd-Catalyzed Substitution Reaction with 1,3-Dibromo-1-propene (15) and Sodium 4-Methoxyphenoxide (Products 2c and 16c). 16c.** $^1$H NMR ($CDCl_3$, 300 MHz): δ 6.82 (br s, 8H), 6.41 (m, 4H), 4.65 (d, $J$ = 5.1 Hz, 2H), 4.41 (d, $J$ = 5.1 Hz, 2H), 3.75 (s, 6H). IR (neat) 3066, 3040 cm$^{-1}$. HRMS: calcd for $C_{10}H_{11}BrO_2$ $[(^{79}Br)M]^+$ 241.99423, found 241.99358; calcd for $C_{10}H_{11}BrO_2$ $[(^{81}Br)M]^+$ 243.99223, found 243.98381.

**Pd-Catalyzed Substitution Reaction with 1,3-Dibromo-1-propene (15) and Sodium 4-Chlorophenoxide (Products 2d and 16d). 16d Trans (Major) Isomer.** $^1$H NMR ($CDCl_3$, 300 MHz): δ 7.25 (d, $J$ = 8.8 Hz, 2H), 6.84 (d, $J$ = 8.8 Hz, 2H), 6.41 (m, 2H), 4.69 (d, $J$ = 3.7 Hz, 2H). $^{13}$C NMR ($CDCl_3$, 75 MHz): δ 156.80, 130.79, 129.41, 126.10, 115.99, 110.12, 66.50. IR (neat): 3085 cm$^{-1}$. HRMS: calcd for $C_9H_8ClBrO$ [(Cl = 35; Br = 79)M]$^+$ 245.94474, found 245.94575; calcd for $C_9H_8ClBrO$ [(Cl = 35; Br = 81)M]$^+$ 247.94274, found 247.94324.

**16d Cis (Minor) Isomer.** $^1$H NMR ($CDCl_3$, 300 MHz): δ 7.24 (d, $J$ = 8.8 Hz, 2H), 6.82 (d, $J$ = 8.8 Hz, 2H), 6.53−6.37 (m, 2H), 4.45 (d, $J$ = 5.2 Hz, 2H). $^{13}$C NMR ($CDCl_3$, 75 MHz): δ 156.72, 132.32, 129.46, 126.30, 116.06, 109.67, 67.89.

**Pd-Catalyzed Substitution Reaction with 1,3-Dibromo-1-propene (15) and Sodium 4-(Methylcarboxy)phenoxide. 16g Trans (Major) Isomer.** The product was isolated as white crystals, mp = 47−49 °C.

$^1$H NMR ($CDCl_3$, 300 MHz): $\delta$ 7.99 (d, $J$ = 8.68 Hz, 2H), 6.90 (d, $J$ = 8.67 Hz, 2H), 6.52 (d, $J$ = 13.82 Hz, 1H), 6.44 (m, $J$ = 19.18 Hz, 1H), 4.53 (d, $J$ = 5.4 Hz, 2H), 3.88 (s, 3H). $^{13}$C NMR ($CDCl_3$, 75 MHz): $\delta$ 166.67, 161.72, 131.83, 131.63, 123.21, 114.21, 109.95, 67.54, 51.87. IR (neat): 3020, 1714 cm$^{-1}$.

**16g Cis (Minor) Isomer.** The product was isolated as white crystals, mp = 50−52 °C. $^1$H NMR ($CDCl_3$, 300 MHz): $\delta$ 7.99 (d, $J$ = 8.67 Hz, 2H), 6.92 (d, $J$ = 8.69 Hz, 2H), 6.42 (m, 2H), 4.76 (d, $J$ = 2.99 Hz, 2H), 3.88 (s, 3H). $^{13}$C NMR ($CDCl_3$, 75 MHz): $\delta$ 166.70, 161.86, 131.60, 130.42, 123.05, 114.24, 110.37, 66.30, 51.84. IR (neat): 1714 cm$^{-1}$.

**Pd-Catalyzed Substitution Reaction of (*Z*)-1,3-Dibromo-2-deuterio-1-propene (17) with Nondeuterated Sodium Phenoxide (2a and 18).** Following the general procedure for the preparation of **2a**, 146 mg of **17** (0.73 mmol), 172 mg of phenol (2.5 equiv, 1.82 mmol), 44.0 mg of NaH (3.0 equiv, 73 mg of 60% dispersion in mineral oil, 1.82 mmol), and 42.0 mg of $(PPh_3)_4Pd$ (0.05 equiv, 0.036 mmol) in 15 mL of THF provided, after purification by flash chromatography (straight pentane, $R_f$ = 0.25), 88 mg of **2a** (54% yield) and 41 mg of **18** (27% yield). The spectral data of **2a** are given above. The presence of deuterium in the propene fragment is readily spotted by $^1$H and $^{13}$C NMR spectroscopy, as well as HRMS, and there is clearly no detectable level of deuterium in any of these spectra for the 1,2-diphenoxy-2-propene product of this reaction. Spectral data for **18** are identical to those of **16a**, except, of course, for the C2 deuterium. Representative $^1$H NMR chemical shifts for **18** are provided here for the inseparable *E* and *Z* isomers. $^1$H NMR ($CDCl_3$, 300 MHz): $\delta$ 7.32 (m, 4H), 7.00−6.87 (m, 6H), 6.45 (br s, 1H), 6.40 (br s, 1H), 4.71 (s, 2H), 4.43 (s, 2H).

**Pd-Catalyzed Substitution Reaction of 1,3-Dibromo-1-propene (15) with Perdeuterated Sodium Phenoxide (19a, 19b, 19c, and 20).** Following the general procedure for the preparation of **2a**, 100 mg of **15** (0.50 mmol), 151 mg of perdeuterated phenol (3.0 equiv, 1.51 mmol), 36.0 mg of NaH (3.0 equiv, 60 mg of 60% dispersion in mineral oil, 1.51 mmol), and 29.0 mg of $(PPh_3)_4Pd$ (0.05 equiv, 0.025 mmol) in 9.0 mL of THF provided, after purification by flash chromatography (straight pentane, $R_f$ = 0.25), 50.1 mg of **19a**, **19b**, and **19c** (42% yield) and 30.7 mg of **20** (28% yield). The spectral data of **19a**, **19b**, and **19c** are given below on the inseparable mixture. $^1$H NMR ($CDCl_3$, 300 MHz): $\delta$ 4.66 (s, 4H, **19a** and **19c**, PhO−C*H*$_2$−), 4.64 (s, 1H, **19b**, PhO−C*H*D−), 4.61 (br s, 2H, **19b** and **19c**, =C*H*H), 4.26 (d, $J$ = 2.0 Hz, 2H, **19b** and **19c**, =CD*H*), 4.25 (s, 1H, **19a**, =CH*H*). $^{13}$C NMR ($CDCl_3$, 75 MHz): $\delta$ 158.37 (s), 158.17 (s), 154.96 (s), 129.12 (t, $J$ = 24.41 Hz), 128.93 (t, $J$ = 24.41 Hz), 123.76 (t, $J$ = 24.41 Hz), 120.69 (t, $J$ = 24.41 Hz), 120.23 (t, $J$ = 24.41 Hz), 114.62 (t, $J$ = 24.41 Hz), 91.32 (s), 91.08 (t, $J$ = 24.41 Hz), 67.47 (s), 67.17 (t, $J$ = 24.41 Hz). IR (neat): 2360, 2342 cm$^{-1}$. HRMS: calcd for $C_{15}H_3D_{11}O_2$ $[M]^+$ 237.16843, found 237.16833. Spectral data for **20** are identical to those of **16a**, except for the phenoxy-$d_5$ moiety. Representative $^1$H NMR chemical shifts for **20** are provided here for the inseparable cis and trans isomers. $^1$H NMR ($CDCl_3$, 300 MHz): $\delta$ 6.45−6.37 (m, 4H), 4.71 (d, $J$ = 4.8 Hz, 2H), 4.43 (d, $J$ = 4.2 Hz, 2H).

**Pd-Catalyzed Substitution Reaction with 1,3-Dibromo-1-propene (15) and Sodium Phenoxide in the Presence of $D_2O$ (21a, 21a, 2a, and 16a).** Into a 10-mL test tube were added 8 mL of dry THF and 38.4 mg of NaH (3.0 equiv, 60 mg of 60% dispersion in mineral oil, 1.50 mmol). Then, 141 mg of phenol (3.0 equiv, 1.50 mmol) was added slowly to control $H_2$ gas evolution, after which 30.2 mg of $D_2O$ (3.0 equiv, 1.50 mmol) and 29.0 mg of $(PPh_3)_4Pd$ (0.05 equiv, 0.025 mmol) were added. After the mixture was stirred for 5 min, 100 mg of 1,3-dibromo-1-propene (0.50 mmol) was added via syringe, and the reaction's progress was monitored by TLC. Following the workup outlined for **2a**, the reaction provided, after purification by flash chromatography (straight pentane, $R_f$ = 0.25), 46 mg of **2a**, **21a**, and **21b** (40% combined yield) and 24 mg of **16a** (22% yield) as a mixture of cis and trans isomers. The spectral data of **2a** and **16a** are given above. The $^1$H NMR spectrum of the mixture revealed an identical peak pattern between 4 and 5 ppm for deuterated (i.e., **21a** and **21b**) and nondeuterated (i.e., **2a**) 1,2-diphenoxy-2-propene derivatives. Representative spectral data are provided here. $^1$H NMR ($CDCl_3$, 300 MHz): $\delta$ 7.38−7.25 (m, 12H), 7.17−7.04 (m, 9H), 7.02−6.93 (m, 9H), 4.66 (s, 4H, **2a** and **21a**, PhO−C*H*$_2$−), 4.64 (s, 1H, **21b**, PhO−C*H*D−), 4.61 (br s, 2H, **21a**, =C*H*D; **21b** and **2a**, =C*H*H), 4.26 (d, $J$ = 2.0 Hz, 2H, **21b** and **2a**, =CD*H*), 4.25 (s, 1H, **21a**, =CH*H*).

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**Supporting Information Available:** $^1$H or $^{13}$C NMR spectra for all compounds prepared in this study (40 pages, print/PDF). See any current masthead page for ordering information and Web access instructions.

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