Retention of Configuration and Regiochemistry in Allylic Alkylations via the Memory Effect

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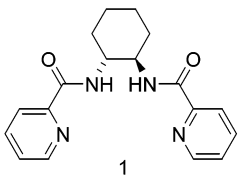
The results of a systematic variation of achiral monodentate ligands used for the Pd-catalyzed alkylation of crotyl and 3-buten-2-yl acetates and carbonates are presented. A significant degree of retention of regiochemistry and stereochemistry was observed for these substrates, especially for nonracemic 3-buten-2-yl ethyl carbonate with PCy_xPh_{3-x} and carbene ligands.

Introduction

A number of different metals have been successfully employed as catalysts for the alkylation of allylic substrates[1] and have been shown to promote the reaction with varying regioselectivity. Iridium and rhodium complexes have recently been used when substitution on the more substituted allyl terminus was desired.[2,3] Furthermore, molybdenum-based catalysts have given excellent results with diaminocyclohexane-based ligands,[4,5] such as **1**, allowing the regio- and enantioselective alkylation of aryl allyl carbonates **2** (Scheme 1) with the production of a preponderance of the branched isomer.



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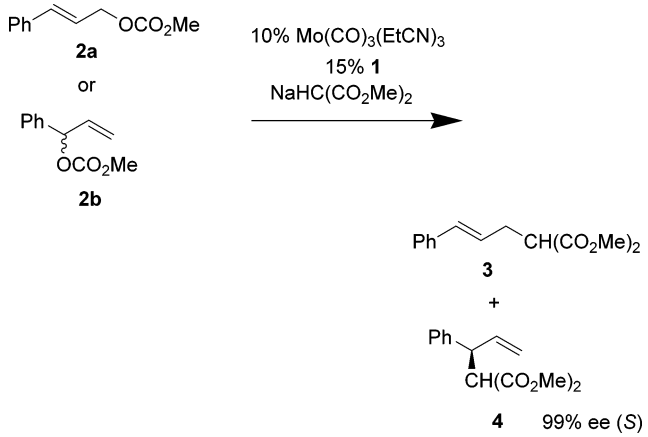
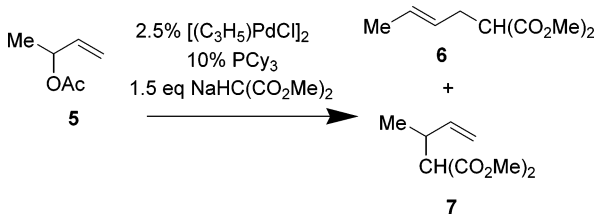
On the other hand, palladium-based catalysts are usually chosen when alkylation at the less substituted terminus of an allyl is desired.[6] There are cases, however, where this selectivity can be changed, particularly by ligand modification, such that the opposite regioselectivity is observed.[7−9] More specifically, the use of PCy_3 as a ligand for the Pd-catalyzed alkylation of racemic 3-buten-2-yl acetate (**5**) has been shown to promote the formation of the branched product **7** (Scheme 2).[10] This is an example of a "*memory effect*", *wherein the original site of attachment of the leaving group plays a significant role in determining the regiochemistry of the product.* This contrasts with a pattern that is frequently seen for palladium catalysts with other phosphorus donor ligands, particularly chelates,

Scheme 1. Mo-Catalyzed Enantioselective Alkylation of 2[a]



[a] The branched isomer (**4**) is produced selectively: **4**:**3** = 49:1.

Scheme 2. Memory Effect Observed When Using PCy_3 as a Ligand for Palladium, Producing a Preponderance of 7 (7:6 = 92:8)



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10.1021/om0306224 CCC: $27.50
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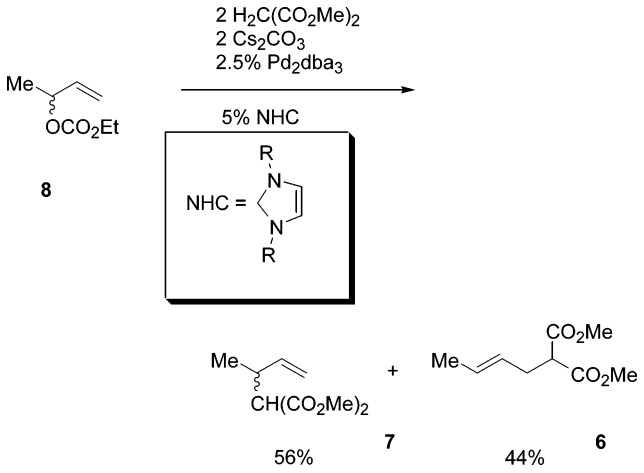
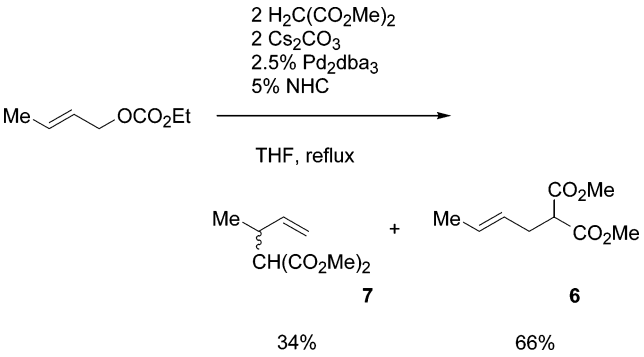
Scheme 3. Memory Effect Observed When Using (t-Bu)$_2$NHC as a Ligand for Pd, Producing an Excess of 7



Scheme 4. Products Observed When Using (t-Bu)$_2$NHC as a Ligand for Pd, Producing an Excess of the Linear Product



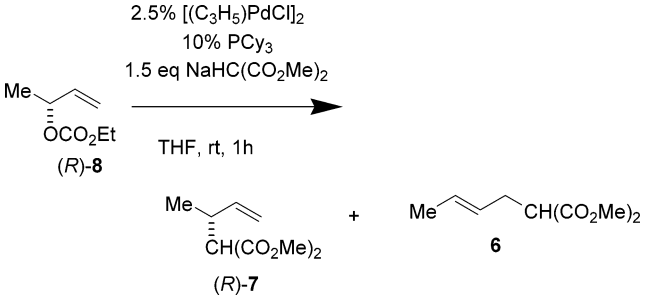
where the original point of attachment of the leaving group is irrelevant and regioselectivity is controlled by the ligand set. The absence of a memory effect is an important feature in the operation of asymmetric allylation catalysts, as stereocontrol based on the position of attachment of the leaving group, rather than the influence of the chiral ligands, would reduce the enantioselectivity of the catalyst.

Results

We have observed a memory effect similar to that shown in Scheme 3 for the carbonate analogue of **5** with Pd/PCy$_3$ (which yields **7**:**6** = 87:13). We have also found that a modest memory effect can be observed using the carbonate analogue of **5** as a substrate and N-heterocyclic carbenes (NHC's) as ligands and for which a **7**:**6** ratio of 56:44 was observed for (t-Bu)$_2$−NHC and 57:43 was observed for (i-Pr$_2$C$_6$H$_3$)$_2$−NHC (Schemes 3 and 4). This contrasts with the result using the linear carbonate and (t-Bu)$_2$−NHC, which gave a **7**:**6** ratio of 34:66.

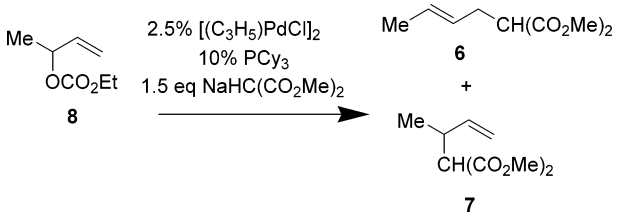
It is reasonable to expect that when a regiochemical memory effect exists, it could also involve a memory effect in terms of stereochemistry. Thus, there are two facets to this phenomenon: (1) a *regiochemical memory effect* and (2) a *stereochemical memory effect*. One isolated instance of partial chirality retention was previously observed with a nonracemic acetate in the reaction shown in Scheme 2;[11] however, no comment about its significance was made at that time. We sought to investigate this phenomenon in analogous reactions such as that shown in Scheme 3, and thus, we required a nonracemic branched carbonate as a substrate for these studies.

Scheme 5. Stereochemical Memory Effect Using PCy$_3$ as a Ligand for Pd[a]



[a] The branched isomer is formed in excess (87:13) with predominant retention of configuration.

Table 1. Stereochemical Memory Effect Using a PCy$_3$/Pd Catalyst



ee of **8** (R), %	PCy$_3$:Pd	nucleophile:**8**	ee of **7** (R). %
89	2	1.5:1	79
91	2	1.5:1	82
91	3	1.5:1	72
91	2	3.0:1	82

Compound (R)-**8** can be prepared in high enantiomeric purity from the commercially available, though expensive, (R)-3-buten-2-ol. We also found that nonracemic **8** could be prepared via kinetic resolution (see Experimental Section). With nonracemic **8** in hand, we sought to investigate the stereochemistry of the memory effect in the palladium-catalyzed reaction.

We examined the palladium-catalyzed alkylation of the allylic carbonate **8** using PCy$_3$ as the ligand. When (R)-(+)-**8** was utilized, we found that the reaction yielded (R)-(+)-**7** (Scheme 5). Table 1 summarizes the effects of changing the nucleophile or the PCy$_3$ loading on the ee of the alkylated product.

We also examined the effect of using less bulky phosphines containing both phenyl and cyclohexyl groups. The results are summarized in Table 2. Generally, Ph$_3$P-containing catalysts are presumed to not have a large memory effect;[6] however, we have observed that if the reactions are run at room temperature or below there can be a significant regiochemical memory effect that is more pronounced with carbonates relative to acetates. One should note that the crotyl carbonate still yields a significant amount of branched product (41%), whereas we observed that crotyl acetate shows only 17% branched product.

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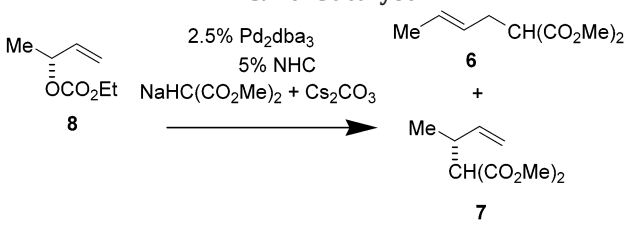
Table 2. Comparison of Memory Effects Observed with Substrate 8 and Shown by Different Phosphines

ee (*R*) of substrate, %	*T*, °C	phosphine ligand (10%)	B:L[a]	ee (*R*) of product, %
0	−78[b]	PPh_3	62:38	0
0	−24	PPh_3	48:52	0
0	23	PPh_3	45:55	0
0	65	PPh_3	39:61	0
0	23	$PCyPh_2$	72:28	0
0	−15	$PCyPh_2$	70:30	0
0	23	PCy_2Ph	81:19	0
0	23	PCy_2biphenyl	61:39	0
91	23	$PCyPh_2$	69:31	25
91	23	PCy_2Ph	81:19	79
91	25	PCy_3	87:13	82

[a] The reactions were performed in thf with 1.5 equiv of $NaHC(CO_2Me)_2$. [b] Held at −78 °C for 4 days and then warmed to 23 °C.

Table 3. Stereochemical Memory Effect Using NHC/Pd Catalyst[a]



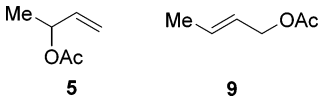
ee of **8** (*R*), %	NHC:Pd	NHC	ee of **7** (*R*), %	**6**:**7**
91	1	$(t\text{-Bu})_2$NHC	68	61:39
91	1	$(i\text{-Pr}_2\text{Ph})_2$NHC	66	66:34

[a] 100% conversion was observed after 20 h of heating under reflux in thf.

Using the in situ generated carbene following the procedure of Sato et al.,[12] we observed significant retention of configuration indicating a high stereochemical but only a modest regiochemical memory effect (Table 3).

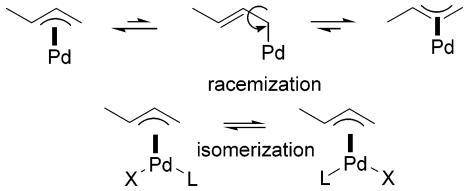
Discussion

For palladium-catalyzed reactions, the usual presumption is that the regiochemistry of the product is independent of the isomeric nature of the substrate. For example, in the presence of PPh_3 (2:1 P:Pd), crotyl acetate (**9**) and 3-buten-2-yl acetate (**5**) both yield a similar linear-to-branched ratio of 81:19 and 82:18, respectively, when the nucleophile was $[CH_3C(CO_2Me)_2]^-$.[13] The position of attachment of the leaving group



in this case appears to be generally irrelevant, owing to the rapid formation of the same distribution of reactive η^3-allylic intermediates after oxidative addition prior to nucleophilic attack. An $\eta^3-\eta^1-\eta^3$ allyl interconversion often provides a pathway for racemization of an allylic palladium intermediate (Scheme 6).[14] Thus,

Scheme 6. Racemization via $\eta^3-\eta^1-\eta^3$ Allyl Interconversion and Cis−Trans Isomerization of an η^3-Allyl Intermediate



neither retention of regiochemistry nor retention of stereochemistry was observed.

The $Na[CH_3C(CO_2Me)_2]$ reaction, however, is deceptive, since the bulkiness of the nucleophile biases the attack on the less hindered terminus and tends to yield linear product. We found that, on carrying out the reaction with $Na[HC(CO_2Me)_2]$ in thf in the presence of PPh_3 (2:1 P:Pd), crotyl acetate (**9**) and 3-buten-2-yl acetate (**5**) yielded linear-to-branched ratios of 83:17 and 58:42. respectively, which indicate a definite regiochemical memory effect for PPh_3-containing catalysts.

In the presence of the bulky monodentate ligand 2-(diphenylphosphino)-2′-methoxy-1,1′-binaphthyl (MeO-MOP), Hayashi found that a greater retention of regiochemistry could be observed in alkylations. Thus, crotyl acetate and 3-buten-2-yl acetate yielded linear-to-branched ratios of 95:5 and 38:62, respectively, in the presence of 2:1 MeO-MOP:Pd.[13] This was attributed to the large cone angle[15] (>210°) of MeO-MOP, which would favor intermediate complexes containing one phosphine. Even though an excess of phosphine was present in this case, only the neutral (allyl)Pd(L)X was formed. The excess MeO-MOP was not effective in promoting cis−trans isomerization. The cone angle of Cy_3P is still large (170°)[15] but not as large as that of MeO-MOP, and so a similar mechanism presumably holds. Generally one would not expect a carbene to dissociate easily, so that a bulky carbene should behave similarly.

When oxidative addition occurs, Hayashi suggests that the leaving group (OAc in his case) remains cis to the carbon to which it was originally attached. If cis−trans isomerism is slow, then attack occurring trans to the phosphine[16−18] should result in the regiochemistry being retained.

This also could provide a rationale for the retention of regiochemistry and stereochemistry with **8** and PCy_3 and other bulky phosphines, if $\eta^3-\eta^1-\eta^3$ allyl interconversion at the unsubstituted terminus were slow. This is unexpected because, if the phosphine were trans to the methyl, it would promote racemization via an η^1-crotyl group, as shown in Scheme 6. A phosphine generally weakens the bond trans to it and promotes formation of an η^1-crotyl group cis to the phosphine ligand. On the other hand, if the phosphine were cis to the methyl, a σ-bond would be formed at the more

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(15) Tolman, C. A. *Chem. Rev.* **1977**, *77*, 313.
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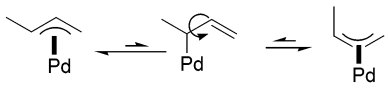
(17) Jonasson, C.; Kritikos, M.; Backvall, J.-E.; Szabo, K. J. *Chem. Eur. J.* **2000**, *6*, 432.
(18) Faller, J. W.; Sarantopoulos, N. Unpublished X-ray crystallographic results, manuscript in preparation.

Scheme 7. Syn−Anti Isomerization via $\eta^3-\eta^1-\eta^3$ Allyl Interconversion



substituted terminus. This does not provide a path for racemization but only isomerization. Since the syn isomer is thermodynamically more stable,[13] this path would only provide for a small concentration of the anti isomer and the configuration at carbon remains the same (Scheme 7). The most important feature, however, is that an excess of a bulky phosphine does not promote a kinetically important alternative route for racemization. There is significant interaction between the phosphine and the methyl so that, given the possibility of reaching cis−trans equilibrium, a single isomer (>90%) would predominate. We found by NMR that (crotyl)Pd(Cy_3P)Cl is a single isomer with the P trans to the methyl *at equilibrium*. In contrast to the results with other less bulky phosphines, a 1.3:1 ratio of **7**:**6** is observed with crotyl acetate;[10] hence, the Cy_3P promotes formation of the branched isomer, even though a memory effect would suggest a predominance of the linear isomer. This may be partially attributed to the directing influence of the trans phosphine in competition with a steric preference for adding to the least substituted terminus.

When structural features do not allow isomerization or racemization of the allyl, retention of the stereochemistry at the alkylated carbon is typical for palladium-catalyzed allylic alkylations in medium-polarity solvents such as THF. Thus, the results are consistent with retention of configuration via either double inversion or double retention *and* a lack of significant racemization in the intermediate. This suggests that capture of the allyl intermediate occurs before racemization can occur. Although Hayashi stresses the importance of the neutral (allyl)Pd(L)X intermediate,[14] others have suggested that a more reactive ion-paired intermediate is more important.[8] With the exception of bulky aliphatic phosphines such as Cy_3P, memory effect studies have focused on phosphines with aromatic substitution. It would appear that the Cy_3P has an ideal combination of (1) bulk that prevents rapid isomerization via a second-order attack on an allyl intermediate by a second phosphine, (2) electronic properties that provide for slow isomerization and racemization, and (3) basicity to promote rapid oxidative addition of the carbonate. Although it has been suggested that a bis MeO-MOP Pd complex is unlikely, owing to steric effects,[14] we have isolated $(Cy_3P)_2PdCl(CH_2Cl)$ from mixtures of [(allyl)PdCl]$_2$ and excess PCy_3 in CH_2Cl_2.[18] This attests to the ease of oxidative addition of $(Cy_3P)_nPd^0$ and the potential stability of a bis Cy_3P complex that could be involved in the catalytic cycle. The Pd−C bond lengths we have observed in (allyl)Pd(PCy_3)Cl (**10**) of 2.19 Å trans to P and 2.11 Å trans to Cl suggests that attack should occur trans to P in analogous compounds based on studies indicating that attack occurs at the more weakly bound carbon atom.[17,18] Similar conclusions can be drawn from (allyl)Pd[(*i*-$Pr_2Ph)_2$NHC]Cl[19] and (allyl)Pd(*t*-Bu_2NHC)Cl (**11**) which have Pd−C bond lengths of 2.21 and 2.16 Å trans to NHC and 2.10 and 2.10 Å trans to Cl, respectively. We feel that our values for these distances in the *t*-Bu_2NHC complex may be more reliable, because the thermal parameters for the central carbon in the (*i*-$Pr_2Ph)_2$NHC complex suggest some disorder. (crotyl)Pd(Cy_2P-2-biphenyl)Cl (**12**) has Pd−C bond lengths of 2.21 Å trans to P and 2.11 Å trans to Cl.

Needless to say, the reaction pathway is complicated. One might also note that it appears that the distribution of the regioisomers of the products is affected somewhat by the optical purity of the starting material (Table 2 and Scheme 3). For example, note the results for $CyPPh_2$. These results were reproducible when the reactions were repeated, so we do not believe this is an artifact, although there is the possibility that impurities are the basis of the difference. We are continuing to investigate this phenomenon, which could possibly be accounted for by still having product bound in an intermediate when substrate attacks. This observation needs further study but does not significantly change our overall conclusions.

Memory Effects in Perspective. Bosnich[20,21] has provided one of the most comprehensible explanations for the lack of memory effects in many situations. He has elegantly outlined the factors that determine the behavior of a Pd/(*S*,*S*)-chiraphos based allylic alkylation catalyst, and the two key features of his discussion are (1) the fast addition of the allylic substrate on Pd and (2) the rapid equilibration of intermediate Pd complexes that are formed by oxidative addition of the regioisomeric substrates to Pd. The equilibration of a common π-allyl intermediate must occur rapidly relative to the rate at which the nucleophile attacks. The first argument concerns the reactivity of the Pd^0/(*S*,*S*)-chiraphos species toward oxidative addition, while the second argument is the one that requires a single π-allyl intermediate, which subsequently undergoes alkylation. Provided that the rates of the $\eta^3-\eta^1-\eta^3$ rearrangements of a Pd allyl complex which provide the equilibration of the intermediates are dictated by the nature of the ligands, one could argue that ligands such as PCy_3 have the necessary steric and electronic characteristics that produce relative rates that allow deviations from the demands of the Bosnich model.

Fiaud and Malleron[22] reported the first example of a substrate-dependent distribution of products in the catalytic alkylation of allylic substrates in 1981. Their results showed that (1) the enantiomeric purity of the substrate played a role in determining the enantiomeric purity of the product and (2) enantiomeric catalysts gave products of different enantiopurity when a partially optically resolved substrate was used. Since then, a limited number of reports have appeared concerning similar observations, although they were not always explicitly described as a memory effect. Most of them concern Pd-based catalytic systems,[7,10−12,23−27] but this seems to be a more widespread behavior than one might

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(20) Auburn, P. R.; Mackenzie, P. B.; Bosnich, B. *J. Am. Chem. Soc.* **1985**, *107*, 2033−2046.

(21) Mackenzie, P. B.; Whelan, J.; Bosnich, B. *J. Am. Chem. Soc.* **1985**, *107*, 2046−2054.

(22) Fiaud, J. C.; Malleron, J. L. *Tetrahedron Lett.* **1981**, *22*, 1399−1402.

(23) Lloyd-Jones, G. C.; Stephen, S. C. *Chem. Eur. J.* **1998**, *4*, 2539−2549.

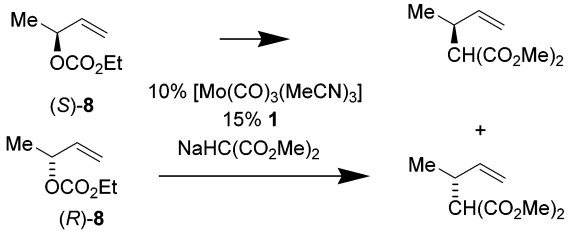
originally have anticipated, and it extends to other metals such as Ru,[28] W,[29] Rh,[3,30,31] Ir,[32,33] and Pt.[34] There are also more complicated rationalizations of the memory effect that involve the active participation of the sodium ion.[25,26]

In conclusion, bulky phosphines are not the only class of ligands that can promote a memory effect in the Pd-catalyzed alkylation of open allylic substrates. N-heterocyclic carbenes are also capable of demonstrating a regioselective memory effect, favoring the formation of the branched product when the branched substrate is employed. Although N-heterocyclic carbenes also show a stereochemical memory effect, this is less pronounced than in the case of Cy_3P and other cyclohexyl-substituted phosphines. For Cy_3P, the use of the ethyl carbonate leaving group improved the observed stereoselectivity of the alkylation, increasing the ee of the product from 64%[11] to 82%. In addition, we have noted that even relatively smaller ligands, such as Ph_3P, can show a regiochemical memory effect, especially when the leaving group is a carbonate and reactions are carried out at lower temperatures. Considering the recent interest in chiral monodentate ligands[35,36] and their potential use in allylic alkylations,[37] there is a great likelihood that memory effects will play a more important role in the observed enantioselectivity than has been observed with bidentate ligands.

Experimental Section

All manipulations were carried out under an inert atmosphere of dinitrogen. THF and acetonitrile or propionitrile were distilled prior to their use over sodium/benzophenone and calcium hydride, respectively. The ligand (+)-**1** (Strem), PCy_3 (Strem), PCy_2Ph (Aldrich), $PCyPh_2$ (Strem), ethyl chloroformate (Aldrich), dimethyl malonate (Aldrich), dimethyl methylmalonate (Aldrich), $Pd_2(dba)_3$ (Strem), Cs_2CO_3 (Strem), $Mo(CO)_6$ (Strem), *rac*-3-buten-2-ol (Fluka), and (*R*)-(−)-3-buten-2-ol (Fluka) were used as received. The palladium dimers $[(C_3H_5)PdCl]_2$ and $[(C_4H_7)PdCl]_2$ are prepared according to a previously published procedure.[38] Spectra were recorded on a Bruker 400 spectrometer. Shift experiments using (+)-Eu(hfc)$_3$ were recorded on a Bruker 500 spectrometer. The enantiomeric excess of **8** in the kinetic resolution experiments was determined by GC using a Hewlett-Packard 5890A gas chromatograph with a Cyclodex-B column. Determinations of optical rotation were performed on a Perkin-Elmer Model 341 polarimeter.

Scheme 8. Kinetic Resolution of the Racemic Carbonate 8



3-But-1-enyl Ethyl Carbonate (8). The procedure that follows was used for making both the racemic **8** and (*R*)-**8**. Into a flame-dried Schlenk flask that was filled with nitrogen were introduced 10 mL of Et_2O, 3-buten-2-ol (200 mg, 2.77 mmol), and pyridine (2−3-fold excess). The resulting mixture was cooled externally by the use of an ice bath. Dropwise addition of ethyl chloroformate (2−3-fold excess) caused the precipitation of pyHCl. After all of the ethyl chloroformate was added, the ice bath was removed and the mixture was stirred at room temperature overnight. Water was added to the reaction mixture, and extraction with ether followed. The combined organic extracts were dried over anhydrous Na_2SO_4, and the ether was evaporated on a rotary evaporator, yielding a pale yellow oil (200 mg, 50% yield). ^{1}H NMR (400 MHz, $CDCl_3$ δ): 5.80 (m, 1H), 5.22 (d, J = 17 Hz, 1H), 5.12 (m, 2H), 4.12 (q, J = 7.2 Hz, 2H), 1.30 (d, J = 6.4 Hz, 3H), 1.24 (t, J = 7.6 Hz, 3H). GC (HP 5890A, Cyclodex-B, 30 °C, He (15 psi)): 72.2 min, (*R*)-**8**; 73.4 min, (*S*)-**8**.

NaHC(CO$_2$Me)$_2$. NaH (200 mg, 8.3 mmol) was suspended in 10 mL of THF contained in a flame-dried Schlenk flask. The flask was externally cooled by the use of an ice bath, and dimethyl malonate (1 g, 7.54 mmol) was added dropwise. After the cessation of hydrogen evolution the mixture was stirred until it became clear. The solvent was evaporated, and the resulting white solid was kept under nitrogen (88% yield).

The following spectra were used to identify products by NMR (see ref 5).

((*E*)-1-But-2-enyl)malonic Acid Dimethyl Ester (6). ^{1}H NMR (300 MHz, $CDCl_3$, δ): 5.61−5.49 (m, 1H), 5.42−5.31 (m, 1H), 3.73 (s, 6H), 3.41 (t, J = 7.5 Hz, 1H), 2.57 (m, 2H), 1.64 (dd, J = 6.1, 1.0 Hz, 3H).

2-(1-Methylallyl)malonic Acid Dimethyl Ester (7). ^{1}H NMR (400 MHz, 25 °C, $CDCl_3$): δ 5.70 (ddd, J = 17.2, 10.4, 8.0, 1H), 5.03 (d, J = 17.2 Hz, 1H), 4.95 (d, J = 10.4 Hz, 1H), 3.67 (s, 3H), 3.63 (s, 3H), 3.25 (d, J = 8.8 Hz, 1H), 2.89 (m, 1H), 1.03 (d, J = 6.8 Hz, 3H).

3-Buten-2-ol via Kinetic Resolution. We investigated the use of $Mo(CO)_3(CH_3CN)_3$ and $Mo(CO)_3(C_2H_5CN)_3$ with the ligand (+)-**1** as a catalyst for the kinetic resolution of the racemic ethyl carbonate **8** (Scheme 8). Particularly with the acetonitrile adduct we found the percent conversion after 15 h to be erratic, but one result (with 0.5 equiv of malonate) showed an ee for **8** of 64% *S* after 47% conversion. In another run for 36 h (with 0.7 equiv of malonate) showed an ee for **8** of 78% *S*. Thus, we anticipated that refinement of the procedure might well provide a route to reasonable quantities of **8** in high enantiomeric purity.

Procedure A. Molybdenum hexacarbonyl (13.12 mg, 0.050 mmol) in 5 mL of acetonitrile was heated under vigorous reflux for 5 h. The solvent was evaporated, and THF (5 mL) that had been degassed by two freeze−pump−thaw cycles was introduced to the reaction flask that contained the fresh $Mo(CO)_3(MeCN)_3$. Addition of (+)-**1** (24.3 mg, 0.075 mmol) to the resulting THF solution afforded a deep violet color. The solution was heated under reflux for 1 h, and then the nucleophile and **8** were added to the reaction mixture, which had been cooled to room temperature. Stirring was continued

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for 15−36 h. Conversions were determined by NMR spectra, integrating the vinylic methyl groups of substrate **8** and products **6** and **7**. The determination of the ee of **8** by GC was performed on an aliquot of the reaction mixture that was added to pentane, filtered through Celite, and dissolved in dichloromethane after evaporation of pentane on a rotary evaporator. The retention times for the two enantiomers of **8** at 30 °C using a Hewlett-Packard 5890A with a Cyclodex-B column and a pressure of 15 psi for He are 72.2 min (*R*) and 73.4 min (*S*).

Procedure B. A sample of $Mo(CO)_3(EtCN)_3$ was prepared by heating 2 g of molybdenum hexacarbonyl in 20 mL of EtCN under reflux for 24 h. The tan powder that was obtained after evaporation of the solvent was stored under N_2, and samples of it were used in the kinetic resolution experiments in place of the MeCN analogue. The reaction workup was exactly the same as in procedure A described above.

Typical Procedure for the Pd-Catalyzed Alkylations of (*R*)-8 using PCy_3 as Ligand. A flame-dried Schlenk flask was charged with THF (10 mL), $[(C_3H_5)PdCl]_2$ (2.2 mg, 0.006 mmol), PCy_3 (6.8 mg, 0.024 mmol), (*R*)-(+)-**8** (35 mg, 0.243 mmol), and $NaHC(CO_2Me)_2$ (56 mg, 0.363 mmol) and then stirred for 1 h at room temperature. Conversions were determined by NMR spectra, integrating the vinylic methyl groups of substrate **8** and product **6** and the allylic methyl group of **7**. The determination of the ee of the alkylated product was performed on an aliquot where the solvent was evaporated on a rotary evaporator and the oily residue was dissolved in pentane and filtered through Celite. The shift reagent (+)-$Eu(hfc)_3$ was used to split the allylic methyl group doublet of the alkylated product **7** (initially at δ 1.03) into two unequal doublets (minor δ 1.59, major δ 1.52), the integrals of which were used to calculate the ee. The sign of rotation of the reaction mixture, +, indicated[5] the presence of (*R*)-(+)-**7** in excess. Thus, the minor doublet at δ 1.59 corresponds to the allylic methyl group on the complex of Eu with (*S*)-(−)-**7**, and the major doublet at δ 1.52 corresponds to the allylic methyl group on the complex of Eu with (*R*)-(+)-**7**.

Typical Procedure for the Pd-Catalyzed Alkylations of (*R*)-8 using $NHC(t\text{-}Bu)_2$ as Ligand. A flame-dried three-necked flask equipped with a condenser was charged with THF (5 mL), $Pd_2(dba)_3$ (5.6 mg, 0.006 mmol), NHC-t-Bu (2.2 mg, 0.012 mmol), (*R*)-(+)-**8** (35 mg, 0.243 mmol), $H_2C(CO_2Me)_2$ (64.2 mg, 0.485 mmol), and Cs_2CO_3 (158 mg, 0.48 mmol), and the mixture was heated under reflux for 20 h. Conversions were determined by NMR spectra, integrating the olefinic protons of substrate **8** and products **6** and **7**. The determination of the ee of the alkylated product was performed on an aliquot where the solvent was evaporated on a rotary evaporator and the oily residue was dissolved in pentane and filtered through Celite. The shift reagent (+)-$Eu(hfc)_3$ was used to split the anti olefinic proton doublet of the alkylated product **7** to two unequal doublets, whose integrals were used to calculate the ee. The sign of rotation of the reaction mixture, +, indicated[5] the presence of excess (*R*)-(+)-**7.** When the major doublet was shifted to δ 5.27, it corresponded to the olefinic anti proton of (*R*)-(+)-**7**, and the less shifted minor doublet at δ 5.19 corresponded to the olefinic anti proton of (*S*)-(−)-7.

Preparation of (allyl)PdCl(L) and (crotyl)PdCl(L) Complexes. The following procedure was used for the preparation of (η^3-*syn*-crotyl)$PdCl(PCy_3)$. All other allyl and crotyl complexes were prepared in over 90% yield by analogous manipulations. Crystals for use in X-ray crystal studies were obtained by slow diffusion of pentane into a toluene solution of each complex.

(η^3-*syn*-crotyl)$PdCl(PCy_3)$. A Schlenk flask was flame-dried and charged with $[(crotyl)PdCl]_2$ (25.0 mg, 0.063 mmol) and PCy_3 (35.6 mg, 0.127 mmol). THF (10 mL) was introduced using a syringe, and the very pale yellow solution was stirred at room temperature for approximately 1 h. Evaporation of THF on a rotary evaporator and repeated washing of the resulting pale yellow residue with pentane afforded the product as an off-white powder in high yield (57 mg, 94% yield). ^{1}H NMR (400 MHz, $CDCl_3$, δ): 5.12 (1H, ddd, H_c, J = 12.0 Hz, J = 11.6 Hz, J = 6.8 Hz), 4.26 (1H, ddq, $H_{a'}$, J = 6.8 Hz, J(Me−H) = 6.8 Hz, J(P−H) ≈ 7 Hz), 3.16 (1H, dd, H_s, J = 6.8, 2.0 Hz); 2.37 (1H, d, H_a, J = 11.6 Hz), 2.15−1.21 (36H, m, Cy and crotyl Me resonances). The spectrum showed less than 3% of other isomers. $^{31}P\{^1H\}$ NMR (202 MHz, $CDCl_3$, δ): 43.5 (s) for the syn isomer. No other isomers were observed. Anal. Calcd for $C_{22}H_{40}ClPPd$: C, 55:35; H, 8.45. Found: C, 54.26; H,8.32. Multiple analysis attempts deviated from the calculated values. We were unable to obtain satisfactory analyses.

(η^3-allyl)$PdCl(PCy_3)$ (10). ^{1}H NMR (400 MHz, $CDCl_3$, δ): 5.32 (1H, m, H_c), 4.54 (1H, ddd, H_s, J(PH) = 8.0, 8.0, 2.0 Hz), 3.50 (1H, dd, H_a, J = 11.7 Hz, J(PH) = 8.8 Hz); 3.33 (1H, d, $H_{s'}$, J = 6.4 Hz, J ≈ 2 Hz), 2.52 (1H, d, $H_{a'}$, J = 12.0 Hz), 2.14−1.12 (33H, m, Cy resonances). $^{31}P\{^1H\}$ NMR (162 MHz, $CDCl_3$, δ): 41.9 (s). Anal. Calcd for $C_{21}H_{38}ClPPd$: C, 54.43; H, 8.27. Found: C, 54.28; H, 8.24.

(η^3-*syn*-crotyl)PdCl(dicyclohexylphosphino-2-biphenyl) (12). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 4.45 (1H, br, H_c), 3.87 (1H, br, H_a), 2.88 (1H, d, $H_{s'}$, J = 6.5 Hz), 2.34−1.10 (26H, m, Cy, $H_{a'}$ and crotyl Me resonances). $^{31}P\{^1H\}$ NMR (122 MHz, $CDCl_3$, δ): 31.4 (s). Anal. Calcd for $C_{28}H_{38}ClPPd$: C, 61.43; H, 7.00. Found: C, 61.44; H, 7.05.

(η^3-C_3H_5)PdCl(1,3-di-*tert*-butyl-imidazol-2-ylidene) (11). ^{1}H NMR (400 MHz, $CDCl_3$, δ): 7.13 (1H, d, NC*H*CHN, J = 2.2 Hz), 7.11 (1H, d, NCHC*H*N, J = 2.2 Hz), 5.25 (1H, m, H_c), 4.11 (1H, dd, H_s, J = 7.2, 2.0 Hz), 3.37 (1H, d, H_s, J = 6.4 Hz), 3.28 (1H, d, H_a, J = 12.8 Hz), 2.26 (1H, d, H_a, J = 11.6 Hz), 1.86 (9H, s, $C(CH_3)_3$), 1.69 (9H, s, $C(CH_3)_3$). Anal. Calcd for $C_{14}H_{25}N_2ClPd$: C, 46.29; H, 6.94; N, 7.71. Found: C, 46.58; H, 7.05; N, 7.54.

X-ray Crystallography of (allyl)$PdCl(PCy_3)$, (allyl)-$PdCl(NHC(t\text{-}Bu)_2)$, and (crotyl)$PdCl(PCy_2$biphenyl) (10−12). Data were collected on a Nonius KappaCCD (Mo Kα radiation). The structures were solved by direct methods (SIR92)[39] and refined on *F* for all reflections using the TEXSAN[40] package. Non-hydrogen atoms were refined with anisotropic displacement parameters. Hydrogen atoms were included at calculated positions. One should note that the hydrogen atoms attached to allyl carbons were treated by assuming them to be methylene hydrogen atoms on a Pd−C−C fragment. This provides a more realistic placement of the anti protons than would be obtained by assuming the terminal allyl hydrogen atoms are in the plane of the C−C−C fragment of the allyl. This choice can affect the Pd−C distance by ∼0.01 Å and is an important consideration if comparing distances with other published structures where the choice for calculating positions is not known. Relevant crystal and data parameters are presented below. ORTEP diagrams are shown in Figures 1−3. One should note that many allyl−Pd complexes cocrystallize with small percentages of other isomers in the lattice and this can influence the accuracy of the bond lengths. Both **10** and **12** crystallize with small percentages of other isomers. The nature of the superpositions of atoms suggests that bond length errors would be small. We also noted more complicated disorders in (crotyl)$PdCl(PCy_3)$ and (2-methylallyl)$PdCl(NHC(t\text{-}Bu)_2)$, which made the metrical parameters less reliable.

The colorless compound **10** crystallized in a primitive orthorhombic cell with the dimensions a = 19.1477(5) Å, b = 11.3394(4) Å, c = 9.9827(4) Å, and V = 2167.48(11) Å^3 for Z = 4 and FW = 463.36, with a calculated density of 1.420 g/cm^3 and an absorption coefficient μ(Mo Kα) of 10.55 cm^{-1}. A large

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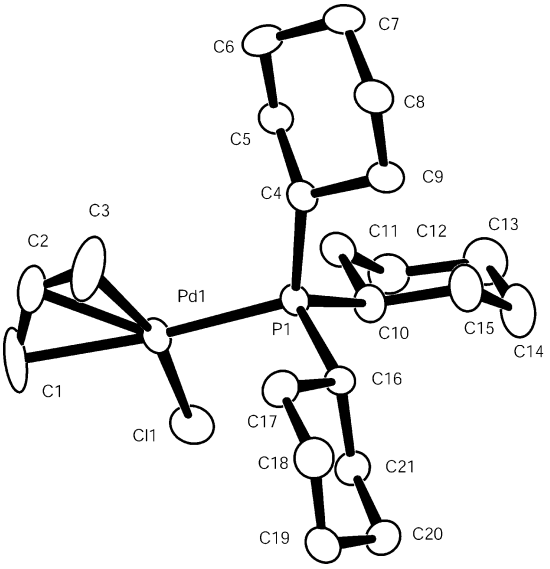

Figure 1. ORTEP view of **10** with 50% probability ellipsoids. Selected distances are as follows: Pd1−Cl1, 2.369(2); Pd1−P1, 2.304(1); Pd1−C1, 2.191(6); Pd1−C2, 2.115(8); Pd1−C3, 2.112(6).

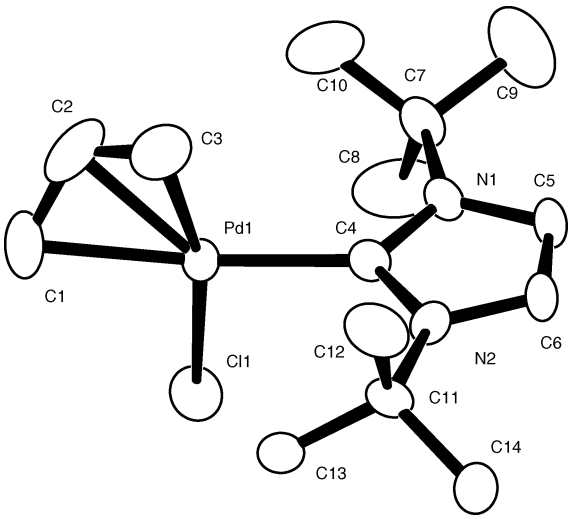

Figure 2. ORTEP view of **11** with 50% probability ellipsoids. Selected distances are as follows: Pd1−Cl1, 2.379(2); Pd1−C1, 2.162(7); Pd1−C2, 2.118(7); Pd1−C3, 2.101(6).

crystal was used, and the data were corrected (SORTAV).[41] The systematic absences of *0kl* ($k + l = \pm 2n + 1$) and *h0l* ($h = \pm 2n + 1$) determined the space group to be $Pna2_1$ (No. 33) or centrosymmetric *Pnam* (No. 62). Ultimately, the solution in $Pna2_1$ (No. 33) was successful. The polarity was determined by inverting the structure, which gave higher R factors (R = 0.0284 and R_w = 0.0330 compared to R = 0.0273 and R_w = 0.0314). The final cycle of full-matrix least-squares refinement on F was based on 1771 observed reflections ($I > 3.00\sigma(I)$) and 220 variable parameters and converged with unweighted and weighted agreement factors of R = 0.027 and R_w = 0.031.

The yellow compound **11** crystallized in a primitive orthorhombic cell with dimensions a = 11.0410(5) Å, b = 9.9613(4) Å, c = 14.3349(6) Å, and V = 1576.59(10) Å^3 for Z = 4 and FW = 363.22, with a calculated density of 1.530 g/cm^3 and an absorption coefficient, μ(Mo Kα), of 13.34 cm^{-1}. The systematic absences of *0kl* ($k + l = \pm 2n + 1$) and *h0l* ($h = \pm 2n + 1$) determined the space group to be $Pna2_1$ (No. 33) or centrosymmetric *Pnam* (No. 62). Ultimately, solution in $Pna2_1$ (No. 33) was successful. The polarity was determined (marginally, suggesting a possible racemic twin) by inverting the structure, which gave higher R factors (R = 0.0335 and R_w = 0.0327 compared to R = 0.0331 and R_w = 0.0326). The final cycle of full-matrix least-squares refinement on F was based on 1479 observed reflections ($I > 2.00\sigma(I)$) and 162 variable parameters and converged with unweighted and weighted agreement factors of R = 0.033 and R_w = 0.033.

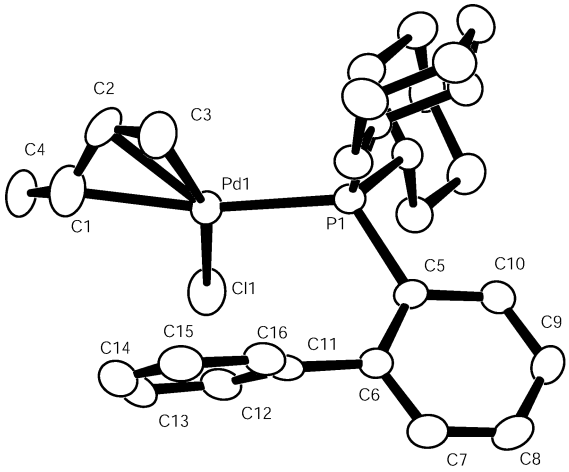

Figure 3. ORTEP view of **12** with 50% probability ellipsoids. Selected distances are as follows: Pd1−Cl1, 2.375(1); Pd1−C1, 2.214(4); Pd1−C2, 2.118(7); Pd1−C3, 2.132(3). Note that there is a 9% population of the anti isomer present, which is not shown.

The pale yellow compound **12** crystallized in a primitive monoclinic cell with dimensions a = 10.3007(3) Å, b = 13.3964(5) Å, c = 19.1082(8) Å, and V = 2587.5(2) Å^3 for Z = 4 and FW = 363.22, with a calculated density of 1.405 g/cm^3 and an absorption coefficient, μ(Mo Kα), of 8.96 cm^{-1}. The systematic absences of *h0l* ($l = \pm 2n + 1$) and *0k0* ($k = \pm 2n + 1$) uniquely determined the space group to be $P2_1/c$ (No. 14). The solution was straightforward, but the final difference Fourier map showed two peaks near C1. These suggested cocrystallization of an anti crotyl isomer bound to the opposite face of the allyl with the methyl trans to the phosphorus. Carbon atoms at these peak positions were refined isotropically including the occupancy, with the constraint that their occupancies were equal and their sum with the occupancies of their counterparts, C2 and C4, totaled 1.000. This led to a refined occupancy of 9.1% for the minor isomer. The final cycle of full-matrix least-squares refinement on F was based on 2456 observed reflections ($I > 3.00\sigma(I)$) and 280 variable parameters and converged with unweighted and weighted agreement factors of R = 0.032 and R_w = 0.032.

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Supporting Information Available: Tables of bond distances and angles, anisotropic thermal parameters, and atomic coordinates for **10**−**12**. This material is available free of charge via the Internet at http://pubs.acs.org.

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