Stereo- and Regiocontrol in Palladium-Catalyzed Allylic Alkylation Using 1,10-Phenanthrolines as Ligands

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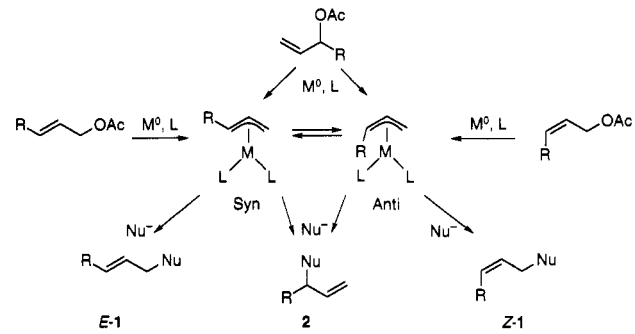
A series of 2,9-disubstituted-1,10-phenanthroline type ligands have been used in palladium-catalyzed displacement of allylic acetates. It was found that intermediate *syn*- and *anti*-(η^3-butenyl)palladium complexes reacted with different rates and regiochemistries. Depending on the ligands, this could be used for regiocontrol as well as stereocontrol. With the parent 1,-10-phenanthroline, syn complexes were formed quickly as intermediates from both (*E*) and (*Z*) allylic acetates, leading to nearly exclusive formation of (*E*) products. In contrast, complete retention of alkene stereochemistry was observed with 2,9-dimethyl-1,10-phenanthroline which also gave a catalyst with a considerably higher activity than catalysts based on triphenylphosphine.

Palladium-catalyzed allylic subsitution is extensively used in synthetic organic chemistry.[1] It is generally accepted that the reaction proceeds via an (η^3-allyl)-palladium complex which reacts with the nucleophile to give an alkene, as outlined in Scheme 1.

The product formed will depend on the stereochemistry of the η^3-allyl complex (syn or anti) and the regiochemistry of the nucleophilic attack. Thus, nucleophilic addition to the unsubstituted terminus of a syn complex will give an (*E*)-alkene, and addition to an anti complex will produce a (*Z*)-alkene. (η^3-Allyl)palladium complexes undergo anti–syn isomerization, which may be rapid.[2] Therefore, it should be possible to prepare (*E*) or (*Z*) products from either (*E*)- or (*Z*)-acetates, provided that suitable ligands could be used to control the stereochemistry of the intermediate (η^3-allyl)palladium complexes (Scheme 1). Although exceptions are known,[3] in terminally substituted η^3-allyl systems, the syn isomer dominates. We have recently discovered that certain bidentate planar ligands, such as 2,9-dimethyl-1,10-phenanthroline (dmphen), can induce a preference for the anti isomer by destabilizing the syn configuration.[4] Auxiliary nitrogen ligands have been sparsely used in palladium-catalyzed nucleophilic

Scheme 1



substitution but the interest is currently increasing.[5] In order to study the possibility for the general use of phenanthroline ligands in stereo- and regiocontrol, we have made an extensive investigation of the effects of 2,9-substituents in the catalytic displacement of allylic acetates.

Results and Discussion

Stoichiometric Reactions. The regio- and stereochemistry and relative reactivities of pure syn and anti complexes were first studied. The syn and anti isomers of (2,9-dimethyl-1,10-phenanthroline)(η^3-butenyl)palladium tetrafluoroborate, *syn*-**3a** and *anti*-**3a**, were prepared in >95% stereochemical purity and reacted with the diethyl methylmalonate anion in DMF. Completely different product patterns were obtained, essentially pure (*E*) alkene ((*E*)-**1**) from *syn*-**3a** and a 40/60 mixture of (*Z*)-alkene ((*Z*)-**1**) and terminal alkene (**2**) from *anti*-**3a** (Table 1, entries 1 and 2). From these results one can

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(1) (a) Tsuji, J. *Organic Syntheses with Palladium Compounds*; Springer Verlag: Heidelberg, 1980. (b) Trost, B. M.; Verhoeven, T. R. In *Comprehensive Organometallic Chemistry*; Wilkinson, G., Ed.; Pergamon: Oxford, U.K., 1982; Vol. 8, pp 799–938. (c) Heck, R. F. *Palladium Reagents in Organic Synthesis*; Academic Prss: New York, 1985. (d) Collman, J. P.; Hegedus, L. S.; Norton, J. R.; Finke, R. G. *Principles and Applications of Organotransition Metal Chemistry*; University Science Books: Mill Valley, CA, 1987. (e) Frost, C. G.; Howarth, J.; Williams, J. M. J. *Tetrahedron: Asymmetry* **1992,** *3,* 1089. (f) Godleski, S. A. In *Comprehensive Organic Synthesis*; Trost, B. M., Ed.; Pergamon: Oxford, U.K., 1991; Vol. 4, p 585. (g) Consiglio, G.; Waymouth, R. *Chem. Rev.* **1989,** *89,* 257. (h) Trost, B. M. *Angew. Chem., Int. Ed. Engl.* **1989,** *28,* 1173.

(2) For a review, see: Vrieze, K. *Dynamic Nuclear Magnetic Resonance Spectroscopy*; Jackman, M., Cotton, F. A., Eds.; Academic Press: New York, 1975; p 441.

(3) (a) Faller, J. W.; Thomsen, M. E.; Mattina, M. J. *J. Am. Chem. Soc.* **1971,** *93,* 2642. (b) Lukas, J.; Ramakers-Blom, J. E.; Hewitt, T. G.; De Boer, J. J. U. *J. Organomet. Chem.* **1972,** *46,* 167. (c) Ohta, T.; Hosokawa, T.; Murahashi, S. I.; Miki, K.; Kasai, N. *Organometallics* **1985,** *4,* 2080.

(4) (a) Akermark, B.; Hansson, S.; Vitagliano, A. *J. Am. Chem. Soc.* **1990,** *112,* 4587. (b) Sjögren, M.; Hansson, S.; Norrby, P.-O.; Akermark, B.; Cucciolito, M. E.; Vitagliano, A. *Organometallics* **1992,** *11,* 3954.

(5) (a) Leutenegger, U.; Umbricht, G.; Fahrni, C.; von Matt, P.; Pfaltz, A. *Tetrahedron* **1992,** *48,* 2143. (b) Togni, A. *Tetrahedron: Asymmetry* **1991,** *2,* 683. (c) Bovens, M.; Togni, A.; Venanzi, L. M. *J. Organomet. Chem.* **1993,** *451,* C28. (d) Srinz, J.; Helmchen, G. *Tetrahedron Lett.* **1993,** *34,* 1769. (e) Frost, C. G.; Williams, J. M. J. *Tetrahedron Lett.* **1993,** *34,* 2015. (f) Dawson, G. J.; Frost, C. G.; Williams, J. J. J.; Coote, S. J. *Tetrahedron Lett.* **1993,** *34,* 3149.

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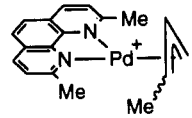
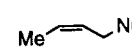
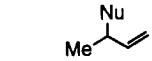
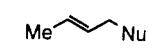
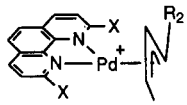
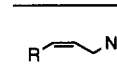
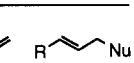
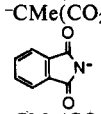
Table 1. Stoichiometric Reactions with (η^3-2-Butenyl)palladium Tetrafluoroborate[a]

entry		nucleophile	% yield 		
1	*syn*-**3a**	$^-CMe(CO_2Et)_2$	0	1	99
2	*anti*-**3a**	$^-CMe(CO_2Et)_2$	40	60	0
3	*syn*-**3a**	$^-CH(CO_2Me)_2$	2	15	83[b]
4	*anti*-**3a**	$^-CH(CO_2Me)_2$	24	43	33[b]
5	*syn*-**3a**	$^-CH(CO_2Me)(SO_2Ph)$	8	8	84[b]
6	*anti*-**3a**	$^-CH(CO_2Me)(SO_2Ph)$	21	19	60[b]
7	*syn*-**3a**	$^-CH(SO_2Ph)_2$	14	6	80
8	*anti*-**3a**	$^-CH(SO_2Ph)_2$	14	6	80

[a] The reaction conditions were 0 °C and 2 equiv of nucleophile in DMF. The product distribution was measured by GC. In a few representative cases the products were isolated and the chemical yield was found to be over 90%. [b] 10–20% diallylated product.

Table 2. Stoichiometric Reactions with Different (η^3-Allyl)palladium Complexes[a]

entry		R	complex (%)[b]	nucleophile	solvent	% yield 		
1	X = C≡C—Me	R_1 = Me; R_2 = H	*anti*-**4a** (>95)[c]	$^-CMe(CO_2Et)_2$	DMF	52	28	20
2	X = C≡C—Me	R_1 = Me; R_2 = H	*anti*-**4a** (>95)[c]	$^-CMe(CO_2Et)_2$	DMF	51	25	24
3	X = C≡C—Me	R_1 = Me; R_2 = H	*anti*-**4a** (>95)[c]		DMF	67	14	19
4	X = C≡C—Me	R_1 = Me; R_2 = H	*anti*-**4a** (>95)[c]		DMF	69	18	13
5	X = *n*-Bu	R_1 = Me; R_2 = H	*syn*-**5a** (95)[c]	$^-CMe(CO_2Et)_2$	DMF	3	9	88
6	X = *n*-Bu	R_1 = Me; R_2 = H	*anti*-**5a** (55)[c]	$^-CMe(CO_2Et)_2$	DMF	31	21	48
7	X = Me	R_1 = CH_2OMe; R_2 = H	*anti*-**3b** (90)[d]	$^-CMe(CO_2Et)_2$	DMF	84	5	11
8	X = Me	R_1 = CH_2OMe; R_2 = H	*anti*-**3b** (90)[d]	$^-CMe(CO_2Et)_2$	MeOH	74	0	26
9	X = C≡C—Me	R_1 = CH_2OMe; R_2 = H	*anti*-**4b** (85)[d]	$^-CMe(CO_2Et)_2$	DMF	68	0	32
10	X = C≡C—Me	R_1 = Ph; R_2 = H	*anti*-**4c** (60)[d]	$^-CMe(CO_2Et)_2$	DMF	34	16	50
11	X_1 =  ; X_2 = H	R_1 = Me; R_2 = H	*syn*-**6a** (>95)[c]	$^-CMe(CO_2Et)_2$	DMF	5	6	89
12	X = H	R_1 = Me; R_2 = H	*syn*-**7a** (90)[d]	$^-CMe(CO_2Et)_2$	DMF	6	8	86
13	Ph_3P	R_1 = Me; R_2 = H	*syn*-**8a** (90)[d]	$^-CMe(CO_2Et)_2$	DMF	7	14	79
								
14	X = Me	R_1 = R_2 = Me	1-*anti*-3-*syn*-**3d**[c,e]	$^-CMe(CO_2Et)_2$	MeOH	98	2	

[a] The reaction conditions were 0 °C and 2 equiv of nucleophile in DMF. The product distribution was measured by GC. In a few representative cases the products were isolated and the chemical yield was found to be over 90%. [b] Isomeric purity of the complex. [c] BF_4^- as counterion. [d] $CF_3CO_2^-$ as counterion. [e] 84% of anti–syn, 16% of syn–syn.

draw two interesting conclusions. First, when the dmphen ligand is used, nucleophilic attack is faster than syn–anti isomerization leading to a retention of the stereochemistry of the η^3-allyl system. Second, the syn complex reacts exclusively at the unsubstituted η^3-allyl terminus while the anti complex shows a slight preference for the more substituted terminus (ratio substituted/unsubstituted ca. 3/2). This difference in the reactivity pattern is probably due to the trajectory of the attacking nucleophile, which brings it closer to the syn substituent,[6] thus leading to unfavorable nonbonded interactions when this is an alkyl group (*syn*-**3a**) rather than hydrogen (*anti*-**3a**). It clearly offers an unexpected possibility for regiocontrol and perhaps could also be used to induce chirality in monosubstituted η^3-allyl systems which so far has not been possible with palladium.

With a less hindered nucleophile, the dimethyl malonate anion, and *anti*-**3a**, the relative ratio between reaction at the substituted over unsubstituted position is decreased to approximately 2/3 instead of the expected increase (Table 1, entry 4). This can be explained by partial isomerization, as suggested by the formation of considerable amounts of (*E*)-product. The result might seem surprising but is in accordance with earlier studies which show that the methyl substituted malonate reacts faster than malonate.[7,8] With bulkier nucleophiles, *e.g.* when one of the alkoxycarbonyl groups of the malonate has been replaced by a phenylsulfonyl group, the product pattern shows that the rate of syn–anti isomerization approaches that of nucleophilic attack. Finally, when both alkoxycarbonyl groups are replaced by phenylsulfonyl groups, the isomerization is faster than nucleophilic addition, as shown by the formation of the same product composition from both *syn*- and *anti*-**3a**. The (*E*)-alkene formed from reaction at the less substituted position of the syn complex is the major product in these reactions (Table 1, entries 5–8).

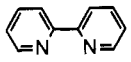
A few complexes with ligands other than 2,9-dimethyl-1,10-phenanthroline (dmphen) and/or different allyl systems were also studied (Table 2). Because the propynyl

(6) Trost, B. M.; Lautens, M. *Tetrahedron* **1987**, *21*, 4817.

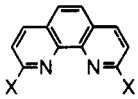
(7) Trost, B. M.; Lautens, M. *J. Am. Chem. Soc.* **1987**, *109*, 1469.

(8) The rate of addition was decreasing in the order of diethyl methylmalonate > dimethyl methylmalonate > diethyl malonate ≈ dimethyl malonate in DMF when cyclohexenyl acetate was used as the allylic substrate and (2,9-dimethyl-1,10-phenanthroline)[(1,2,3-η)-2-butenyl]palladium tetrafluoroborate as catalyst.

Table 3. Palladium-Catalyzed Nucleophilic Substitution of (*E*)-1-Acetoxy-2-hexene Using Sodium Diethyl Methylmalonate in DMF[a]

entry	ligand		leaving group	% yield		
				Pr–=–Nu	Pr–CH(Nu)–=–	Pr–=–Nu
1	X = H[b]	**7**	OAc	4	0	96
2	X = Me[b]	**3**	OAc[c,d]	0	0	100
3		**9**	OAc	4	0	96
4	PPh_3 (2 equiv)	**8**	OAc	3	1	96
5	PPh_3 (4 equiv)[e]	**10**	OAc[f]	0	0	100

[a] The standard reaction conditions were 1 mmol of allylic acetate, 2 mmol of sodium diethyl methylmalonate, 1 mol % of Pd (as $[Pd(C_4H_7)OTFA]_2$, and 5 mol % of the ligand in 3 mL of DMF. [b] Ligand structure for entries 1 and 2:



[c] Only 1 mol % of ligand was used. [d] Reaction was complete after 10 min. [e] $Pd(PPh_3)_4$ used as catalyst. [f] 84% yield after 19 h.

substituted ligand had earlier been shown to induce even higher anti selectivity than the dmphen ligand,[4b] *anti*-**4a** was reacted with the diethyl methylmalonate anion (Table 2, entries 1 and 2). Some isomerization occurred, as shown by the formation of ca. 20% of (*E*) product. The reaction gave a low ratio (2/5) of addition to the substituted vs the unsubstituted terminus. The use of a nitrogen nucleophile, the phthalimide anion, which should be less bulky but perhaps less reactive than the malonates, led to a ca. 20% isomerization and an even lower substituted/unsubstituted (1/5) ratio (Table 2, entries 3 and 4). Again the result is not quite the expected, but it is encouraging in terms of selective preparation of the (*Z*)-alkene which is the major product despite the isomerization.

Some exploratory experiments with complexes **5a** of the 2,9-dibutyl substituted phenanthroline ligand were also performed. The pure syn complex gave ca. 90% (*E*) product, indicating some isomerization. Because the anti complexes **5a** was only 55% isomerically enriched, no definite conclusion can be made. However, the result is compatible with formation of (*E*)-alkene from the syn isomer and a 2/3 mixture of terminal alkene and (*Z*)-alkene from the anti isomer (Table 2, entries 5 and 6).

A phenyl substituted η^3-allyl system behaved largely as the simple crotyl system (Table 1, entry 10), but with the η^3-4-methoxybutenyl complex, a high preference for the less substituted η^3-allyl terminus was observed. Thus, the complex *anti*-**3b** (90% isomeric purity) gave 84% preference for reaction at this position when dmphen was the ligand (Table 2, entry 7), indicating high regioselectivity. This is similar to the earlier results from nucleophilic addition to 1,3-dienes where essentially exclusive 1,4 addition was observed.[9] A possible explanation is the repulsion of the nucleophile by the methoxy group. The selectivity is affected by the solvent, and a change from DMF to methanol leads to a slower reaction and increased isomerization (Table 1, entry 8). With the bulky 2,9-dipropynyl ligand, the (*Z*)/(*E*) ratio decreases further due to isomerization and only ca. 68% (*Z*) product was obtained (Table 2, entry 9).

A comparison was made between the reactivities of a series of syn complexes with ligands of varying steric requirements and electronic demand (Table 2, entries 11–13). Compared to the dmphen complex (Table 1, entry 1), the parent phenanthroline complex (**7**), or the complex with the mono(methoxynaphthyl)substituted ligand (**6a**), all gave lower selectivity for the (*E*)-alkene. This is also true for the complex **8a**, where the triphenylphosphine ligand is used. In the latter case, a slight increase in the preference for reaction at the more substituted allyl terminus was observed, in accordance with the acceptor character of the ligand.[10]

The counterion had an influence on the rates, as would be expected, and a slightly slower reaction was observed with trifluoroacetate as the counterion relative to tetrafluoroborate. A moderate further decrease would be anticipated with acetate, which is the expected counterion in the catalytic reaction with allylic acetates. As expected from a detailed study of the dynamic processes of (phenanthroline)palladium allyl complexes,[11] the rate of syn–anti isomerization is also affected. For example, in DMF solution, the isomerization of the pure syn complex **3a** (BF_4^- as counterion) to the equilibrium mixture (syn/anti ca. 1/4) took more than 48 h at 21 °C. This time was decreased to ca. 1 h with trifluoroacetate as the counterion. Addition of 0.1 equiv of chloride decreases the time for equilibration to approximately 0.5 h.

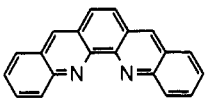
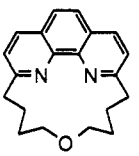
Because it is probable that both syn and anti complexes are generally present at equilibrium, their relative reactivity is very important. A competitive experiment was performed by reacting a 1/1 mixture of *syn*- and *anti*-**3a** (counterion BF_4^-) with 50 mol % of the diethyl methylmalonate anion. The syn complex was found to be more reactive (relative rates 7/1). This result can perhaps be partly explained by the higher stability of the anti isomer. An experiment was also done with the η^3-1-methylbutenyl complex **3d**, which has the 1-anti-3-syn configuration (ca. 85%), permitting competition between syn and anti configurations within the same molecule. In the reaction with diethyl methylmalonate, **3d** gave exclusively (98%) the (*E*) product from attack at the terminus with an anti configuration (Table 2, entry 14). This result is consistent

(9) (a) Akermark, B.; Ljungquist, A.; Panunzio, M. *Tetrahedron Lett.* **1981**, *22*, 1055. (b) Bäckvall, J.-E.; Byström, S. E.; Nordberg, R. E. *J. Org. Chem.* **1984**, *49*, 4619.

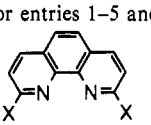
(10) (a) Akermark, B.; Krakenberger, B.; Hansson, S.; Vitagliano, A. *Organometallics* **1987**, *6*, 620. (b) Akermark, B.; Zetterberg, K.; Hansson, S.; Krakenberger, B.; Vitagliano, A. *J. Organomet. Chem.* **1987**, *335*, 133.

(11) Hansson, S.; Norrby, P.-O.; Sjögren, M.; Akermark, B.; Cucciolito, M. E.; Giordano, F.; Vitagliano, A. *Organometallics* **1993**, *12*, 4940.

Table 4. Palladium-Catalyzed Nucleophilic Substitution of (*Z*)-1-Acetoxy-2-hexene Using Sodium Diethyl Methylmalonate in DMF[a]

entry	ligand		leaving group	% yield		
				Pr–CH=CH–Nu	Pr–CH(Nu)–CH=CH$_2$	Pr–CH=CH–CH$_2$–Nu
1	X = H[b]	**7**	OAc	4	0	96
2	X = Me[b]	**3**	OAc	46	49	5
3	X = Me[b]	**3**	OAc[c]	46	48	6
4	X = Me[b]	**3**	OAc[d,e]	46	49	5
5	X = Me[b]	**3**	OTFA	46	49	5
6		**11**	OAc	56	24	21
7	X = *t*-Bu[b]	**12**	OAc		no reaction	
8	X = Me, X = *t*-Bu[b]	**13**	OAc	37	36	27
9	X = H, X = *t*-Bu[b]	**14**	OAc	6	3	91
10	X = Cl[b]	**15**	OAc	10	4	86
11	X = H, X = Cl[b]	**16**	OAc	11	3	86
12	X = H, X = Cl[b]	**16**	OTFA[e]	22	2	77
13	X = C≡N[b]	**17**	OAc		no reaction	
14	X = C≡C—Me[b]	**4**	OAc	29	32	39[g]
15	X = C≡C—Me[b]	**4**	OTFA[e]	26	61	13[h]
16	X = C≡C—Ph[b]	**18**	OAc	18	8	74[g]
17		**19**	OAc	72	22	6
18		**19**	OTFA[e,f]	67	27	6
19	PPh_3 (2 equiv)	**8**	OAc	50	20	30
20	PPh_3 (4 equiv)[i]	**10**	OAc	66	26	8
21	dmphen (5 equiv) + dba[j]		OAc	46	46	8

[a] The standard reaction conditions were 1 mmol of allylic acetate, 2 mmol of sodium diethyl methylmalonate, 1 mol % of Pd (as $[Pd(C_4H_7)OTFA]_2$, and 5 mol % of the ligand in 3 mL of DMF. [b] Ligand structure for entries 1–5 and 7–16:



[c] The reaction temperature was 21 °C. [d] 1 mol % of dmphen was used. [e] The reaction temperature was −18 °C. [f] The reaction was performed in EtOH. [g] 30% conversion after 19 h. [h] 44% conversion after 19 h, 95% after 48 h. [i] $Pd(PPh_3)_4$ was used as catalyst. [j] $Pd(dba)_2$ was used as catalyst.

with the low reactivity of a syn substituted position (Table 1, entry 1), as discussed above.

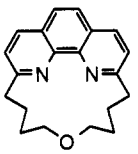
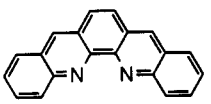
Catalytic Reactions. The major part of the catalytic experiments was run with hexenyl acetates because all three relevant isomers, (*E*)-1-acetoxy-2-hexene, (*Z*)-1-acetoxy-2-hexene, and 3-acetoxy-1-hexene, could be prepared in high isomeric purity from commercially available compounds. They were reacted with the anion of diethyl methylmalonate in the presence of a catalyst generated from bis(trifluoroacetato)bis(η^3-butenyl)palladium and the appropriate auxiliary ligand. Some other substrates and nucleophiles were also investigated, and a few experiments with phosphine based catalysts as well as $Pd(dba)_2$ were done (dba = dibenzylideneacetone). Except where noted, the reactions were run at 0 °C and were conveniently monitored by GC. A few experiments were run at higher (20 °C) or lower (−18 °C) temperatures, but no changes in product patterns were noted. The results are presented in Tables 3–6. The reactions of (*E*)-1-acetoxy-2-hexene reveal some interesting features.

When the dmphen ligand was used, the (*E*) stereochemistry was preserved (>99% (*E*), Table 3, entry 2). With 1,10-phenanthroline (phen) and bipyridine as ligands, the formation of small amounts of (*Z*) product (ca. 4%, Table 3, entries 1 and 3) indicates that isomerization takes place. This was also true when bis(triphenylphosphine)-palladium(0) was used as catalyst (Table 3, entry 4). By contrast, the catalyst tetrakis(triphenylphosphine)palladium(0) induced no isomerization (Table 3, entry 5), but the reaction with a catalyst containing the dmphen ligand is much faster (100% yield in ca. 10 min vs 84% yield in 24 h). Thus, it appears that in DMF dmphen is the superior ligand for preserving (*E*) stereochemistry and at the same time gives the highest catalytic activity in the palladium-catalyzed allylic substitution.

Also with (*Z*)-1-acetoxy-2-hexene as substrate, retention of configuration was observed when dmphen was present as an auxiliary ligand, as shown by the clean formation of the (*Z*) product from the reaction at the least substituted terminus of the intermediate η^3-allyl complex. The major product (ca. 50%) was formed by attack at the more substituted terminus of the η^3-allyl intermediate to give the 3-substituted 1-alkene as the product (Table 4, entries 2–5). In sharp contrast, complete isomerization of the intermediate anti complex and almost exclusive formation of the (*E*)-alkene (95%) was observed with 1,10-phenanthroline present as the auxiliary ligand (Table 4, entry 1). Both results are in good agreement with the observations from the stoichiometric reactions (Table 1, entries 1 and 2; Table 2, entry 12).

The use of dibenzo[*b*,*j*]-1,10-phenanthroline as the ligand in the reaction with (*Z*)-1-acetoxy-2-hexene resulted in a far lower reactivity than that with dmphen and extensive isomerization (Table 4, entry 6). The reason is probably the strong steric interference from the fused rings which in contrast to methyl groups lack conformational

Table 5. Palladium-Catalyzed Nucleophilic Substitution of 3-Acetoxy-1-hexene Using Sodium Diethyl Methylmalonate in DMF[a]

				% yield		
entry	ligand		leaving group	Pr–Nu	Pr(Nu)–CH=CH$_2$	Pr–CH=CH–Nu
1	X = H	**7**	OAc	5	0	95
2	X = Me	**3**	OAc	33	36	31
3	X = Cl	**15**	OAc	5	3	92
4	X = H, X = Cl	**16**	OAc	5	2	93
5	X = *t*-Bu	**12**	OAc		no reaction	
6	X = H, X = *t*-Bu	**14**	OAc	5	2	93
7	X = C≡C—SiMe$_3$	**20**	OAc		no reaction	
8		**19**	OAc	33	12	55
9		**11**	OAc	28	12	60
10	$(PPh_3)_4Pd$	**10**	OAc	19	8	73

[a] The standard reaction conditions were 1 mmol of allylic acetate, 2 mmol of sodium diethyl methylmalonate, 1 mol % of Pd (as $[Pd(C_4H_7)OTFA]_2$, and 5 mol % of the ligand in 3 mL DMF. [b] Ligand structure for entries 1–7:

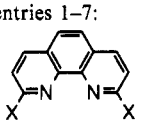
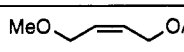
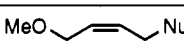
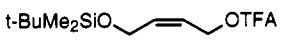
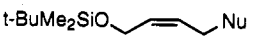
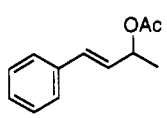
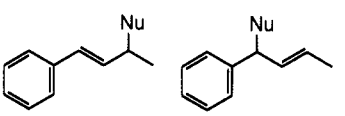
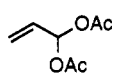
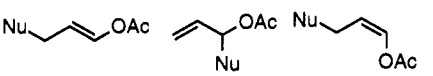


Table 6. Palladium-Catalyzed Allylation of Allylic Acetates Using Sodium Diethyl Methylmalonate in DMF[a]

entry	substrate	product[b]	% isolated yield
1	 >95%[c]		90
2	 **21**	 >95%[c]	91
3	 **22**	 91% 9%	86
4	 **23**	 **24** 71% 22% 7%	94

[a] The standard reaction conditions were 1 mmol of allylic acetate, 2 mmol of sodium diethyl methylmalonate, 1 mol % of Pd (as $[Pd(C_4H_7)OTFA]_2$, and 5 mol % of the ligand in 3 mL of DMF. [b] Isomeric purity determined by GC. [c] Isomeric purity determined by ^1H NMR.

mobility. This is also suggested by the relatively low anti preference (ca. 40%) induced by this ligand.[4b] With the bulky 2,9-*tert*-butyl-1,10-phenanthroline, a catalytically inactive complex was obtained (Table 4, entry 7). In order to explore whether the steric effect of the *tert*-butyl substituent could be used to an advantage, 2-*tert*-butyl-9-methyl-1,10-phenanthroline was prepared and used as the ligand. The intention was that the intermediate would be an anti complex with the more substituted allyl terminus pointing toward the less bulky 9-methyl substituent. Nucleophilic attack at this terminus could then possibly be favored for steric reasons. Contrary to expectations, the relative preference for reaction at the more substituted η^3-allyl position was no greater than that with dmphen. The only major difference was fairly extensive isomerization of the intermediate, as suggested by formation of ca. 25% (*E*) product (Table 4, entry 8). When the mono-*tert*-butyl substituted ligand was used, the result was even more disappointing and ca. 90% (*E*) product was obtained (Table 4, entry 9).

As shown in an earlier study, 2,9-substituents such as chloro, cyano, and propynyl caused higher anti selectivity than methyl.[4b] However, 2,9-dicyano-1,10-phenanthroline gave a complex which was catalytically inactive, while both 2,9-dichloro-1,10-phenanthroline and 2-chloro-1,10-phenanthroline gave catalysts which induced isomerization and produced mainly the (*E*) product (ca. 85%), much as the parent phenanthroline (Table 4, entries 10–13). The propynyl and phenylethynyl) substituted ligands gave catalysts with poor activity which produced low final yields (ca. 40%) and caused extensive isomerization (Table 4, entries 14 and 16). However, when acetate was replaced by trifluoroacetate as the allylic leaving group, the reaction did go to completion with 2,9-dipropynyl-1,10-phenanthroline as the ligand (Table 4, entry 15). The result is interesting in that it shows the highest proportion of

terminal alkene product (ca. 60%) of all the investigated catalysts. Because the stoichiometric reaction of the corresponding crotyl complex gave only ca. 25% of this product (Table 2, entry 2), the result may be due to either transformation of the catalyst or to a change in the reaction path.

In order to explore the effects of connecting the 2,9-substituents by a ring, the macrocyclic ligand **19** was prepared and tested. Essentially no isomerization seemed to take place, and an unusually high ratio (77/23) of attack of the nucleophile on the unsubstituted over the substituted terminus was observed. The reason for this effect is obscure, but it clearly offers a possibility for regiocontrol and selective preparation of (*Z*)-alkenes.

Because $Pd(dba)_2$ is a common source of palladium(0), it was used together with an excess of dmphen and (*Z*)-1-acetoxy-2-hexene as substrate. The same product pattern as without dba was observed, but the reaction was slower (ca. 30 times, Table 4, entry 21). Most likely, dba competes with the substrate for coordination to Pd(0),[12] thus reducing the concentration of the active catalyst.

The reactions of 3-acetoxy-1-hexene essentially corroborate the results from the terminal (*Z*)- and (*E*)-acetates. With ligands found to induce isomerization, such as phen, mono- and dichlorophenanthroline, and mono-*tert*-butylphenanthroline, essentially pure (*E*) product was obtained (Table 5, entries 1 and 3–6). Sterically demanding 2,9-substituents such as *tert*-butyl and (trimethylsilyl)-ethynyl gave inactive catalysts (Table 5, entries 5 and 7). Because the dmphen ligand does not induce isomerization, it is interesting to note that the three possible products are formed in 1/1/1 ratio. This indicates that the oxidative addition occurs with generation of the anti complex preferentially (anti/syn ratio ca. 2/1). In contrast, the macrocyclic ligand **19** and also triphenylphosphine lead to increased formation of (*E*) product (Table 5, entries 2, 8, and 10). This indicates that the formation of syn complex in the oxidative addition becomes favored as the steric requirements of the ligand increase. In principle, these results suggest a new mode of stereocontrol, which will be explored further.

The difference in rates among the catalysts was noticed at an early stage, and a crude comparison was made using 3-acetoxy-1-hexene as a model substrate. The reactions were performed in DMF at 0 °C, and the results are presented in Figure 1.

The ligand which induced the highest reaction rate was dmphen. An excess of the ligand (5 equiv) did not decrease the reaction rate, implying that a bis(2,9-dimethyl-1,10-phenanthroline)palladium(0) complex is not formed. Dmphen gave a higher reaction rate than phenanthroline (ca. 40 times) and also gave a higher reaction rate than 2 and 4 equiv of triphenylphosphine as the ligands (ca. 2 and 160 times, respectively). To the extent that the reactivity is controlled by the relative stabilities of reagents and products,[13] and the rate determining step is the nucleophilic attack (see later), the difference in reaction rates can be ascribed to the known ability of dmphen of destabilizing square-planar coordination environments with respect to trigonal ones.[4,14] A manifestation of the

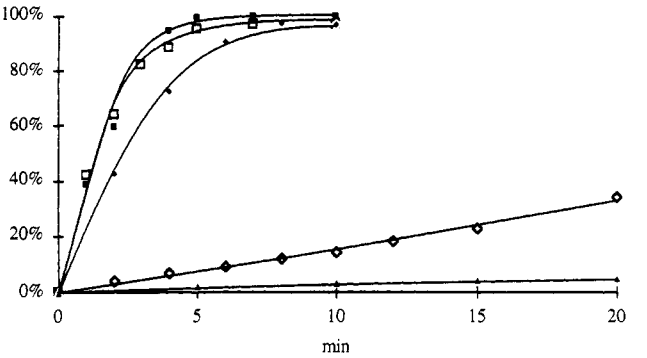


Figure 1. GC yields as function of time when 3-acetoxy-1-hexene was used as substrate: (■) 1 equiv of 2,9-dimethyl-1,10-phenanthroline; (□) 5 equiv of 2,9-dimethyl-1,10-phenanthroline; (♦) 2 equiv of triphenylphosphine; (◇) 1 equiv of 1,10-phenanthroline; (▲) 4 equiv of triphenylphosphine [$Pd(PPh_3)_4$]. Reactions were run in 3 mL of DMF at 0 °C with 0.01 mmol of catalyst, 1 mmol of substrate, 2 mmol of nucleophile.

above effect is the $\Delta G°$ difference for the ligand exchange *syn*-**3a** + phen → *syn*-**7a** + dmphen, which is −20 kJ/mol, while the corresponding difference between the two trigonal Pd(0) model compounds [Pd(dmphen)(dimethyl maleate)] and [Pd(phen)(dimethyl maleate)] is +2 kJ/mol.[15]

It is worth noting that in other catalytic processes in which trigonal intermediates are presumably *not* involved, the presence of substituents at the 2,9-positions of a phenanthroline ligand usually results in a large *decrease* in reactivity.[16] The observation of a reactivity *enhancement* could therefore suggest a reduction of crowding (as for example in a trigonal intermediate) in the rate-determining step of catalytic processes different from allylation. Thus, comparison of the results obtained by using 2,9-disubstituted *versus* unsubstituted phenanthroline might be useful during an investigation of the mechanism of reactions involving square-planar complexes.

Other Substrates. In order to study in an exploratory fashion the general usefulness of dmphen as an auxiliary ligand, a few reactions were performed with more complex allylic acetates. Using (*Z*)-1-acetoxy-4-methoxy-2-butene as substrate, exclusive (>95%) terminal substitution with retention of the stereochemistry was observed (Table 6, entry 1). Similarly, the trifluoroacetate **21** gave terminal substitution with retention (>95%) of the sterochemistry (Table 6, entry 2). The acetate **22** which would give a 1-phenyl-η^3-butenyl complex as an intermediate was found to react predominantly at the methyl substituted η^3-allyl terminus (ratio 10/1) (Table 6, entry 3). Finally, a geminal diacetate (**23**) was used in order to explore the potential for conversion of the diacetate of acrolein into substituted aldehyde precursors. A fair preference, ca. 4/1, for reaction of the less substituted allyl terminus was observed (Table 6, entry 4). Using triphenylphosphine as the ligand, this reaction has been shown earlier to give a ca. 70% yield of **24** as the product.[17] Under our conditions, the yield was increased to 94% but both isomeric products were observed.

(12) Cucciolito, M. E.; Panunzi, A.; Ruffo, F.; De Felice, V. *Gazz. Chim. Ital.* **1989**, *119*, 461.
(13) Akermark, B.; Vitagliano, A. *Organometallics* **1985**, *4*, 1275 and references therein.
(14) Albano, V. G.; Castellari, C.; Cucciolito, M. E.; Panunzi, A.; Vitagliano, A. *Organometallics* **1990**, *9*, 1269.
(15) Cucciolito, M. E.; Vitagliano, A. Unpublished results.
(16) (a) Alessio, E.; Vinzi, F.; Mestroni, G. *J. Mol. Catal.* **1984**, *22*, 327. (b) Cenini, S.; Ragaini, F.; Pizzotti, M.; Porta, F.; Mestroni, G.; Alessio, E. *J. Mol. Catal.* **1991**, *64*, 179. (c) Sen, A.; Jiang, Z. *Macromolecules* **1993**, *26*, 911. (d) Strömberg, S.; Zetterberg, K. Unpublished results.
(17) Trost, B. M.; Vercauteren, J. *Tetrahedron Lett.* **1985**, *26*, 131.

Semicatalytic Reactions. With phen, syn–anti isomerization is faster than nucleophilic attack. Since syn complexes of this ligand are both more abundant and more reactive than the anti complexes, phen is clearly useful for the conversion of a (*Z*) substrate into an (*E*) product. With the dmphen ligand, the rate of syn–anti isomerization is 2 orders of magnitude lower than with phen as the ligand,[11] and syn–anti isomerization was generally observed to be slower than the nucleophilic attack. The formation of a (*Z*) product from and (*E*) substrate is therefore not possible under normal catalytic conditions. A semicatalytic experiment aimed at lowering the concentration of the nucleophile and allowing time for syn–anti isomerization was therefore performed. This was started with the η^3-butenyl complex with the dmphen ligand at equilibrium (syn/anti ca. 1/2). One equivalent of nucleophile was added followed by 1 equiv of (*E*) substrate. The initially formed syn complex was allowed to isomerize to predominantly the anti complex, and the cycle was then repeated 10 times. The result was a partial success in that only 20% of the (*E*) product was obtained, suggesting that ca. 40% reaction took place via the anti complex. A similar result was also obtained from a catalytic experiment, where the nucleophile was added with a syringe pump to a solution of the catalyst and (*E*) substrate.

The reason for the relative yield of product from the anti complex being lower than that expected from the equilibrium mixture was first obscure. However, an examination of direct and indirect information on relative reactivities provides a reasonable explanation and also indicates what has to be changed in order to achieve the desired control. Thus, in the slow addition of nucleophile, the product distribution is that expected from a constant 20% abundance of the ca. 7 times more reactive syn complex. In the batch experiment, if the oxidative addition step occurs at a much higher rate than the nucleophilic attack, fresh syn complex is formed *before* the nucleophile is consumed and will react preferentially, giving the unwanted (*E*) isomer. Therefore, the results from the batch experiment give indirect evidence that the nucleophilic attack is the rate-determining step of the process. In order to support the validity of this conclusion, some crude kinetic experiments were performed, with phen and some related compounds as ligands. Using a few different concentrations of phen and substrate, it could be shown that the rate was strongly dependent on the concentration of the nucleophile but not on the substrate concentration. This is in accordance with rate-determining nucleophilic addition. A few experiments which varied the electron density of the ligand also support this conclusion. Thus, 4,7-dibutoxyphenanthroline, which could generate a more electron rich catalyst, gave a ca. 4 times lower activity than phen. Likewise, a catalyst based on 2,9-dimethoxy-1,10-phenanthroline was ca. 4 times slower than that based on dmphen. If oxidative addition were rate-determining, higher electron density would increase the rate, which is contrary to the experimental result.

Conclusions

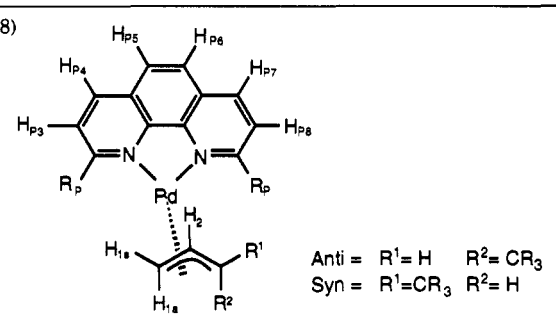
The results show that a catalyst based on the parent phenanthroline is excellent for producing (*E*) products, irrespective of the structure and configuration of the starting alkenyl acetate (Table 3, entry 1; Table 4, entry 1; Table 5, entry 1). Evidently, with this ligand, syn–anti isomerization in the intermediate η^3-allyl complex is faster than nucleophilic addition. On the other hand, the dmphen catalyst is superior in speed and in preservation of stereochemistry. The regioselectivity is low with (*Z*) substrates, except when electronic factors in the η^3-allyl moiety direct the attack (Table 6, entries 1 and 2). The preservation of stereochemistry is in keeping with the reduced rate of syn–anti isomerization in η^3-allyl palladium complexes with the dmphen ligand.[11] The traditional Pd(PPh_3)$_4$ catalyst has a similar influence but the rates are lower by 2 orders of magnitude (cf. Figure 1). The dmphen type ligand is thus exceptional not only because it promotes the formation of anti complexes and preserves the stereochemistry of the substrate but also because it generates a very efficient catalyst. The high activity of the dmphen based catalyst is also interesting because of its mechanistic implications. It can be ascribed to the steric destabilization of the starting square-planar complex relative to the intermediate Pd(0) trigonal species. A comparison between reaction rates when dmphen and the parent phen are present as ligands might be used generally for distinguishing between trigonal and square-planar transition states in a catalytic process.

With regard to the long term goals of our work, the catalytic formation of (*E*) products is clearly possible, using the parent phenanthroline as ligand. A similar selectivity for (*Z*) products is still not at hand. However, the reasons are now fairly well understood and the formation of a ca. 70% (*Z*) product from a (*Z*) substrate, using the macrocyclic ligand **17**, indicates that at least the *preservation* of (*Z*) stereochemistry is possible.

Experimental Section

^{1}H and ^{13}C NMR spectra were recorded on a 400-MHz NMR (Bruker Model AM400) and a 250-MHz NMR (Bruker Model ACF250). ^{1}H NMR chemical shifts are reported in δ (ppm) relative to Me_4Si as an internal standard. ^{13}C NMR chemical shifts are given in δ values relative to the solvent ($CDCl_3$, 77.00 ppm). The following abbreviations are used in descriptions of NMR multiplicities; s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet, app = apparent, br = broadened, J = coupling constant. These subscripts are used: P = phenanthroline protons, s = proton in syn position, and a = proton in anti position relative to H-2. ^{1}H NMR integrations are reported as the relative number of hydrogens (H). NMR assignments were done with a homodecoupling program and were assisted with NOE experiments when necessary. Protons are identified according to the structure shown in ref 18. Because of the straightforward method using in the prepartion of the complexes, ^{1}H NMR data were generally assumed sufficient for full characterization of the compounds, but a few selected elemental analyses were also done. The product mixtures of the catalytic reaction were analyzed by GC (Varian 3700) equipped with an autoinjector (Varian 8000 Autosampler). All phenanthroline derivatives were purified by medium pressure liquid chroma-

(18)



tography (MPLC) as described by Baeckström *et al.*[19] The gel used was Merck aluminum oxide (neutral), and the solvent gradient was a mixture of CH_2Cl_2 and hexane. TLC analysis was performed on Merck aluminum-backed F_{254} aluminum oxide (neutral) plates using UV light for visualization. Melting points were determined in open capillary tubes and are uncorrected. Elemental analyses were performed by Analytische Laboratorien, Engelskirchen, Germany. Unless otherwise stated all solvents and reagents used were purchased from Aldrich, purified, and dried with standard methods.[20]

Ligands Used. 2,9-Dimethyl-1,10-phenanthroline (**3**), 1,10-phenanthroline (**7**), and 2,2′-bipyridine (**9**) were purchased from Aldrich and used as received. 2,9-Dipropynyl-1,10-phenanthroline (**4**),[4b] 2,9-di-*n*-butyl-1,10-phenanthroline (**5**),[21] 2-(8-methoxy-1-naphthyl)-1,10-phenanthroline (**6**),[11] dibenzo[*b,j*]-1,10-phenanthroline (**11**),[22] 2,9-di-*tert*-butyl-1,10-phenanthroline (**12**),[21] 2,9-dichloro-1,10-phenanthroline (**15**),[23] 2-chloro-1,10-phenanthroline (**16**),[4b] 2,9-dicyano-1,10-phenanthroline (**17**),[24] 2,9-bis(phenylethynyl)-1,10-phenanthroline (**18**),[4b] and 2,9-bis((trimethylsilyl)ethynyl)-1,10-phenanthroline (**20**)[4b] were prepared according to literature procedures.

2-*tert*-Butyl-9-methyl-1,10-phenanthroline (13). In an oven dried flask, 2-*tert*-butyl-1,10-phenanthroline (660 mg, 2.8 mmol) was dissolved in THF (15 mL) under a N_2 atmosphere. The stirred solution was cooled to −78 °C, and MeLi (3.4 mmol) was added dropwise over 15 min. After 3 h, 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (772 mg, 3.4 mmol) was added, and the temperature was slowly raised to 20 °C overnight. The THF was removed by rotary evaporation. The crude product was dissolved in CH_2Cl_2 (100 mL) and H_2O (50 mL) followed by a separation. The aqueous phase was extracted three times with CH_2Cl_2. The combined organic phases were dried ($MgSO_4$) and rotary evaporated in vacuo. The crude product was purified by MPLC with aluminum oxide (neutral), yield 554 mg (79%) of **13** as an oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.14 (d, J = 8.5 Hz, 1 H), 8.09 (d, J = 8.2 Hz, 1 H), 7.72 (d, J = 8.5 Hz, 1 H), 7.68 (s, 2 H), 7.45 (d, J = 8.2 Hz, 1 H), 2.92 (s, 3 H), 1.60 (s, 9 H, Me). ^{13}C{H} NMR (100 MHz, $CDCl_3$): δ 169.4, 159.3, 145.8, 144.4, 136.1, 136.0, 126.8, 125.5, 125.3, 123.0, 120.0, 38.7, 30.3, 26.0.

2-*tert*-Butyl-1,10-Phenanthroline (14). In an oven dried flask, 1,10-phenanthroline (5.6 g, 31 mmol) was dissolved in THF (100 mL) under a N_2 atmosphere. The stirred solution was cooled to −78 °C and *t*-BuLi (31 mmol) was added dropwise over 30 min. After 3 h, 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (7.8 g, 34 mmol) was added, and the temperature was slowly raised to 20 °C overnight. The THF was removed by rotary evaporation. The crude material was dissolved in CH_2Cl_2 (200 mL) and H_2O (100 mL) followed by a separation. The aqueous phase was extracted three times with CH_2Cl_2. The combined organic phases were dried ($MgSO_4$) and rotary evaporated in vacuo. The crude product was purified by MPLC with aluminum oxide (neutral), yield 2.18 g (30%) of **14** as an oil that upon storage formed crystals, mp 101 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 9.23 (dd, $J_{P9,P8}$ = 4.4 Hz, $J_{P9,P7}$ = 1.8 Hz, 1 H, H_{P9}), 8.22 (dd, $J_{P7,P8}$ = 8.0 Hz, 1 H, H_{P7}), 8.17 (d, $J_{P4,P3}$ = 8.4 Hz, 1 H, H_{P4}), 7.76 (d, 1 H, H_{P3}), 7.74 (m, 2 H, $H_{P5,P6}$), 7.59 (dd, 1 H, H_{P8}), 1.61 (s, 9 H, Me). ^{13}C{H} NMR (100 MHz, $CDCl_3$): δ 169.8, 150.4, 146.5, 145.0, 136.1, 136.0, 128.9, 126.7, 126.4, 125.6, 122.4, 120.0, 38.6, 30.5. Anal. Calcd for $C_{16}H_{16}N_2$: C, 81.32; H, 6.82. Found: C, 81.12; H, 7.00.

2,9-(6-Oxa-1,11-undecanediyl)-1,10-phenanthroline (19). In an oven dried flask, 2,9-bis(5-hydroxypentyl)-1,10-phenanthroline[25] (201 mg, 0.57 mmol) and ethylene glycol di-*p*-tosylate (210 mg, 0.57 mmol) were dissolved in anhydrous THF (20 mL), and the mixture was aspirated into a syringe. The solution was added slowly (10 h) with a syringe pump to a flask containing a suspension of NaH (60 mg, 2.5 mmol) in anhydrous THF (40 mL) at 55 °C under a N_2 atmosphere. A small amount of H_2O was added to quench the reaction followed by rotary evaporation in vacuo. The crude product was dissolved in H_2O/CH_2Cl_2, and the aqueous phase was extracted three times with CH_2Cl_2. The combined organic phases were dried ($MgSO_4$) and rotary evaporated in vacuo. The crude product was purified by MPLC with aluminum oxide (neutral), yield 117 mg (61%) of **19** as white crystals, mp 111–114 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.09 (d, J = 8.1 Hz, 2 H), 7.68 (s, 2 H), 7.42 (d, J = 8.1 Hz, 2 H), 3.42 (t, J = 5.4 Hz, 4 H), 3.19 (t, J = 6.4 Hz, 4 H), 1.96 (m, 4 H), 1.62 (m, 8 H). ^{13}C{H} NMR (100 MHz, $CDCl_3$): δ 162.6, 145.7, 135.9, 126.8, 125.3, 123.0, 71.0, 38.5, 29.7, 29.3, 26.0. Anal. Calcd for $C_{22}H_{26}N_2O$: C, 79.01; H, 7.84. Found: C, 77.76; H, 7.90. MS, m/z (M^+): calcd 334.46, obsd 334.2.

Synthesis of Complexes. Pd(dibenzylideneacetone)$_2$,[26] (2,9-dimethyl-1,10-phenanthroline)[1,2,3-η)-2-butenyl]palladium tetrafluoroborate (**3a**),[4b] (2,9-dimethyl-1,10-phenanthroline)[(1,2,3-η)-4-methoxy-2-butenyl]palladium trifluoroacetate (**3b**),[4b] (2,9-dimethyl-1,10-phenanthroline)[2-*anti*-4-*syn*-(2,3,4-η)-3-pentenyl]palladium tetrafluoroborate (**3d**),[4b] (2,9-dipropynyl-1,10-phenanthroline)[1,2,3-η)-2-butenyl]palladium tetrafluoroborate (**4a**),[4b] (2,9-dipropynyl-1,10-phenanthroline)[1,2,3-η)-2-butenyl]-palladium trifluoroacetate (**4a**),[4b] (2,9-dipropynyl-1,10-phenanthroline)[1,2,3-η)-4-methoxy-2-butenyl]palladium trifluoroacetate (**4b**),[4b] (2,9-dipropynyl-1,10-phenanthroline)[1,2,3-η)-1-phenyl-2-propenyl]palladium trifluoroacetate (**4c**),[4b] (2,9-di-*n*-butyl-1,10-phenanthroline)[1,2,3-η)-2-butenyl]palladium tetrafluoroborate (**5a**),[4b] (2-(8-methoxy-1-naphthyl)-1,10-phenanthroline)[(1,2,3-η)-2-butenyl]palladium tetrafluoroborate (**6a**),[11] (1,-10-phenanthroline)[1,2,3-η)-2-butenyl]palladium trifluoroacetate (**7a**),[27] and bis(triphenylphosphine)[1,2,3-η)-2-butenyl]palladium trifluoroacetate (**8a**)[27] were prepared using literature procedures. Tetrakis(triphenylphosphine)palladium(0) (**10**) was purchased from Aldrich and used as received. In many cases, (η^3-allyl)-palladium complexes with 2,9-disubstituted-1,10-phenanthrolines as ligands could be isolated in essentially pure syn and anti forms by described procedures.[27] The ^{1}H NMR spectra for the syn and anti forms of the complexes were recorded and assigned from the equilibrium mixture.

Allylic Acetates Used. The following chemicals were bought from Aldrich and used as received: 1-hexen-3-ol, (*Z*)-2-hexen-1-ol, (*E*)-2-hexen-1-ol, and 1,1-diacetoxy-2-propene (**23**). The alcohols were converted to the acetates[28] and trifluoroacetates[29] in good yields using standard procedures. 1-(*tert*-Butyldimethylsiloxy)-(*Z*)-but-2-en-4-ol (**21**),[30] 3-acetoxy-1-phenyl-1-butene (**22**),[31] and 1-methoxy-4-acetoxy-(*Z*)-butene[32] were prepared according to literature procedures.

(*Z*)-1-Acetoxy-2-hexene. Yield: 76%. ^{1}H NMR (250 MHz, $CDCl_3$): δ 5.66–5.45 (m, 2 H), 4.58 (d, J = 6.4 Hz, 2 H), 2.05 (app q, J = 7.1 Hz, 2 H), 2.02 (s, 3 H), 1.37 (app sextet, J = 7.3 Hz, 2 H), 0.87 (t, J = 7.3 Hz, 3 H). ^{13}C{H} NMR (62.5 MHz, $CDCl_3$): δ 171.0, 135.1, 123.5, 60.4, 29.5, 22.5, 21.0, 13.6.

(*E*)-1-Acetoxy-2-hexene. Yield: 72%. ^{1}H NMR (250 MHz, $CDCl_3$): δ 5.74 (br, dt, J_1 = 15.4 Hz, J_2 = 6.6 Hz, 1 H), 5.56 (br dt, J_1 = 15.4 Hz, J_2 = 7.3 Hz, 1 H), 4.88 (d, J = 6.3 Hz, 2 H), 2.12

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(app, q, J = 7.3 Hz, 2 H), 1.38 (app sextet, J = 7.3 Hz, 2 H), 0.88 (t, J = 7.3 Hz, 3 H). $^{13}C\{H\}$ NMR (62.5 MHz, $CDCl_3$): δ 170.8, 136.4, 123.6, 65.3, 34.2, 22.0, 21.0, 13.6.

(*Z*)-1-(Trifluoroacetoxy)-2-hexene. Yield: 82%. ^1H NMR (250 MHz, $CDCl_3$): δ 5.78 (br dt, J_1 = 11.0 Hz, J_2 = 7.4 Hz, 1 H), 5.58 (br dt, J_1 = 11.0 Hz, J_2 = 7.1 Hz, 1 H), 4.88 (d, J = 7.1 Hz, 2 H), 2.12 (app q, J = 7.3 Hz, 2 H), 1.42 (app sextet, J = 7.3 Hz, 2 H), 0.91 (t, J = 7.3 Hz, 3 H). $^{13}C\{H\}$ NMR (62.5 MHz, $CDCl_3$): δ 157.4 (q), 138.1, 120.8, 114.6 (q), 63.6, 29.5, 22.4, 13.5.

3-Acetoxy-1-hexene. Yield: 67%. ^1H NMR (400 MHz, $CDCl_3$): δ 5.76 (ddd, J_1 = 17.2 Hz, J_2 = 10.5 Hz, J_3 = 6.3 Hz, 1 H), 5.25–5.12 (m, 2 H), 2.05 (s, 3 H), 1.65–1.49 (m, 2 H), 1.38–1.28 (m, 3 H), 0.91 (t, J = 7.3 Hz, 3 H). $^{13}C\{H\}$ NMR (62.5 MHz, $CDCl_3$): δ 171.0, 136.6, 116.4, 74.6, 36.3, 21.2, 18.3, 13.8.

1-(*tert*-Butylidmethylsiloxy)-4-(trifluoroacetoxy)-(*Z*)-butene (21). Yield: 85%. ^1H NMR (400 MHz, $CDCl_3$): δ 5.84 (br app quintet, J = 5.5 Hz, 1 H), 5.60 (m, 1 H), 4.96 (dd, J_1 = 6.7 Hz, J_2 = 0.4 Hz, 2 H), 4.31 (dt, J_1 = 5.5 Hz, J_2 = 0.4 Hz, 2 H), 0.90 (s, 9 H), 0.08 (s, 6 H). $^{13}C\{H\}$ NMR (100 MHz, $CDCl_3$): δ 157.3 (q), 136.1, 121.6, 114.4, (q), 63.8, 59.7, 25.8, 18.2, -5.4.

General Procedure of Stoichiometric Alkylation of (η^3-Allyl)palladium Complexes. DMF (0.5 mL) and the nucleophile (2 equiv)[33] were added to an oven dried round-bottom flask under a N_2 atmosphere. The solution was lowered into an ice bath followed by the addition of the substituted (η^3-allyl)-palladium complexes (1 mmol). After 30 min, the flask was taken out of the ice bath and was left at 21 °C. After 2 h, H_2O was added, and the mixture was extracted three times with diethyl ether. The combined organic phases were dried ($MgSO_4$) and rotary evaporated in vacuo.

Identification of the Products from the Stoichiometric Alkylation. Due to the small amount of product formed, the different isomeric products were not separated. Identification of the (*E*) and (*Z*) product was done by observing the coupling constant in ^1H NMR spectroscopy for the double bond (*E*) product $J \approx 15$ Hz and for (*Z*) product $J \approx 11$ Hz). The product derived from internal attack of the nucleophile was determined by the characteristic pattern from the terminal protons in the double bond.[34] Integration in the ^1H NMR spectrum gave an approximate product distribution which was more accurately determined using GC.

General Procedure for Palladium-Catalyzed Alkylation of Hexenyl Acetate. To an oven dried flask were added bis(μ-trifluoroacetato)bis[(1,2,3-η)-2-butenyl]dipalladium[27] (2.7 mg, 0.01 mmol) and a phenanthroline ligand (0.05 mmol), followed by DMF (1 mL) under a N_2 atmosphere. The flask was lowered into an ice bath, and the solution was stirred for 10 min. A premixed mixture of hexenyl acetate (142 mg, 1 mmol) and the internal standard dodecane (70 mg) was added to the flask, followed by a 1 M solution of sodium diethyl methylmalonate in DMF (2 mL, 2 mmol of nucleophile). The reaction was monitored by GC at regular time intervals (5 min, 15 min, 1 h, 5 h, and 19 h) by working up a small aliquot in diethyl ether and H_2O. The product distribution and the yields were determined using the internal standard technique.

(33) DMF solutions of the nucleophile were made in advance.

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Diethyl 2-((*E*)-2-Hexen-1-yl)-2-methylmalonate. ^1H NMR (400 MHz, $CDCl_3$): δ 5.46 (br, dt, J_1 = 15.0 Hz, J_2 = 6.6 Hz, 1 H), 5.25 (br dt, J_1 = 15.4 Hz, J_2 = 7.3 Hz, 1 H), 4.14 (q, J = 7.0 Hz, 4 H), 2.51 (d, J = 7.3 Hz, 2 H), 1.93 (q, J = 6.5 Hz, 2 H), 1.33 (s, 3 H), 1.32 (app sextet, J = 7.5 Hz, 2 H), 1.20 (t, J = 7.0 Hz, 6 H), 0.83 (t, J = 7.3 Hz, 3 H). $^{13}C\{H\}$ NMR (100 MHz, $CDCl_3$): δ 172.0, 135.2, 123.8, 61.0, 53.7, 38.8, 34.6, 22.4, 19.6, 14.0, 13.5.

Diethyl 2-((*Z*)-2-Hexenyl-1-yl)-2-methylmalonate. ^1H NMR (400 MHz, $CDCl_3$): δ 5.53 (m, 1 H), 5.24 (m, 1 H), 4.15 (q, J = 7.0 Hz, 4 H), 2.61 (d, J = 7.5 Hz, 2 H), 2.00 (q, J = 7.3 Hz, 2 H), 1.37 (app sextet, J = 7.5 Hz, 2 H), 1.35 (s, 3 H), 1.22 (t, J = 7.1 Hz, 6 H), 0.88 (t, J = 7.2 Hz, 3 H). $^{13}C\{H\}$ NMR (100 MHz, $CDCl_3$): δ 172.1, 133.7, 122.0, 61.0, 53.5, 33.1, 29.3, 22.6, 19.6, 14.0, 13.8.

Diethyl 2-(1-Hexen-3-yl)-2-methylmalonate. ^1H NMR (400 MHz, $CDCl_3$): δ 5.55 (ddd, J_1 = 17.2 Hz, J_2 = 10.3 Hz, J_3 = 6.3 Hz, 1 H), 5.08–5.00 (m, 2 H), 4.16 (q, J = 7.0 Hz, 4 H), 2.69 (t, J = 10.0 Hz, 1 H), 1.37 (m, 2 H), 1.36 (s, 3 H), 1.23 (t, J = 7.1 Hz, 6 H), 0.87 (t, J = 7.2 Hz, 3 H). $^{13}C\{H\}$ NMR (100 MHz, $CDCl_3$): δ 171.4, 137.2, 118.1, 57.6, 48.7, 48.5, 32.0, 20.8, 19.6, 17.0, 14.0.

General Procedure for Palladium-Catalyzed Alkylation. To an oven dried flask were added bis(μ-trifluoroacetato)bis-[1,2,3-η)-2-butenyl]dipalladium (2.7 mg, 0.01 mmol) and the 2,9-dimethyl-1,10-phenanthroline ligand (0.05 mmol), followed by DMF (1 mL) under a N_2 atmosphere. The flask was lowered into an ice bath, and the solution was stirred for 10 min. Allylic acetate (1 mmol) was added to the flask, followed by a 1 M solution of sodium diethyl methylmalonate in DMF (2 mL, 2 mmol of nucleophile). The reaction was monitored by GC, and when the allylic acetate was consumed, H_2O (15 mL) and diethyl ether (30 mL) were added, followed by a separation. The aqueous phase was extracted three times with diethyl ether. The combined organic phases were dried ($MgSO_4$) and rotary evaporated in vacuo. The crude product was purified by flash chromatography using silica gel with a mixture of petroleum ether and ethyl acetate as eluant.

Diethyl 2-(4-Methoxy-(*Z*)-2-buten-1-yl)-2-methyl)malonate. ^1H NMR (250 MHz, $CDCl_3$): δ 5.68 (br app quintet, J_1 = 11.2 Hz, J_2 = 5.5 Hz, 1 H), 5.46 (m, 1 H), 4.19 (q, J = 6.4 Hz, 4 H), 3.97 (d, J = 6.0 Hz, 2 H), 3.31 (s, 3 H), 2.64 (d, J = 7.6 Hz, 2 H), 1.38 (s, 3 H), 1.23 (t, J = 6.5 Hz, 6 H). $^{13}C\{H\}$ NMR (62.5 MHz, $CDCl_3$): δ 171.8, 130.0, 126.5, 68.0, 61.3, 58.0, 53.3, 33.5, 19.6, 14.0.

Diethyl 2-(4-*tert*-Butyldimethylsiloxy)-(*Z*)-2-buten-1-yl)-2-methylmalonate. ^1H NMR (400 MHz, $CDCl_3$): δ 5.61 (br app quintet, J_1 = 11.3 Hz, J_2 = 5.5 Hz, 1 H), 5.27 (m, 1 H), 4.18 (d, J_1 = 6.5 Hz, 2 H), 4.13 (q, J = 7.2 Hz, 4 H), 2.57 (d, J = 7.8 Hz, 2 H), 1.34 (s, 3 H), 1.20 (t, J = 7.1 Hz, 6 H), 0.85 (s, 9 H), 0.02 (s, 6 H). $^{13}C\{H\}$ NMR (100 MHz, $CDCl_3$): δ 171.8, 133.6, 123.9, 61.3, 59.3, 53.4, 33.5, 25.9, 19.7, 18.3, 14.0, -5.2.

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