Palladium-Catalyzed Arylation of Unsymmetrical Olefins. Bidentate Phosphine Ligand Controlled Regioselectivity

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The palladium-catalyzed arylation of several unsymmetrical olefins by aryl triflates in the presence of bidentate phosphine ligands is described. The use of these ligands increases the influence that electronic factors have in determining the regioselectivity of the reaction. The catalyst performances allow a revisiting of the scheme that describes the regioselectivity outcome in Heck-type reactions. Furthermore, a general mechanism for the palladium-catalyzed arylation of olefins is proposed.

Introduction

One of the most important palladium-catalyzed reactions for carbon–carbon bond formation is the Heck reaction (arylation of olefins);[1] however, the major drawback of this methodology is the low regioselectivity observed with several classes of unsymmetrical olefins. For this reason, the use of other palladium-catalyzed reactions for the functionalization of π-systems are in fashion.[2] On the other hand, these methodologies, where the olefin equivalent is an organometallic derivative, suffer from other drawbacks: the high substrate cost (sometimes the vinyl derivatives are not commercially available) and, for vinyl tin compounds, toxicity.

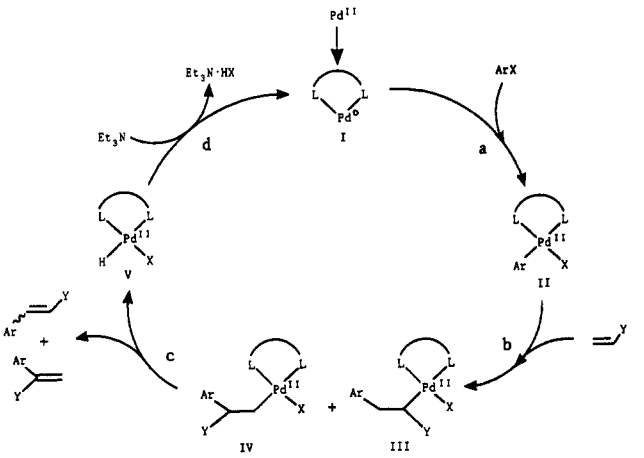
During the course of studies on Heck-type reactions, we found that the use of bidentate phosphine ligands allowed regioselective control in the arylation of acyclic enol ethers.[3]

In particular, the combination of ligands and counterions in the oxidative–addition complex II (Scheme I) steers, independently from other reaction variables, the coordination–insertion step b and consequently the regioselectivity of the arylation (III versus IV).

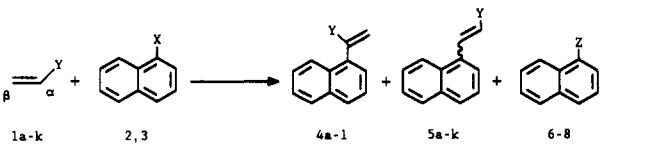
In this paper we report our results on the arylation of other classes of unsymmetrical olefins catalyzed by bidentate phosphines containing catalysts.

The main goal of these studies was to revise the scheme that describes the regioselectivity in Heck-type reactions.[1,4] Furthermore, the use of unsymmetrical olefins gave indirect information on the coordination–insertion step b of the reaction.

Scheme I



Scheme II



X		Y		Y		Z	
2	OTf	a	O-n-But	g	OAc	6	H
3	I	b	$N(CH_2CH_2CH_2CO)$	h	Ph	7	$COCH_3$
		c	$N(CH_3)COCH_3$	i	$N(COCH_2CH_2CO)$	8	$CH_2CH_2COCH_3$
		d	CH_2OH	j	$COOCH_3$	9	CH_2CH_2CN
		e	$CH(OH)CH_3$	k	CN		
		f	CH_2CH_2OH	l	H		

Results

In order to determine the scope and limitations of the use of bidentate phosphine ligands in Heck-type reactions, we have carried out the arylation of several unsymmetrical olefins **1a–k** catalyzed by DPPE-, DPPP-, DPPB-, and DPPF[5]-containing catalysts (Scheme II). Taking advantage of our previous experience we started this investigation by using trifluoromethanesulfonate as leaving group on the aryl moiety.[3,6]

(1) (a) Heck, R. F. *Palladium Reagents in Organic Syntheses*; Academic Press: London, 1985. (b) Heck, R. F. *Org. React.* **1982**, *27*, 345. (C) Heck, R. F. *Pure. Appl. Chem.* **1981**, *53*, 2323. (d) Heck, R. F. *Acc. Chem. Res.* **1979**, *12*, 146. For the arylation of heteroatom-substituted olefins see: (e) Davis, G. D., Jr.; Hallberg, A. *Chem. Rev.* **1989**, *89*, 1433.

(2) For reaction of zinc derivatives see: (a) Neghishi, E.; Luo, F.-T. *J. Org. Chem.* **1983**, *48*, 1560. (b) Russell, C. E.; Hegedus, L. S. *J. Am. Chem. Soc.* **1983**, *105*, 943. (c) Sengupta, S.; Snieckus, V. *J. Org. Chem.* **1990**, *55*, 5680. For reaction of tin derivatives see: (d) Kosugi, M.; Sumiya, T.; Obara, Y.; Suzuki, M.; Sano, M.; Migita, T. *Bull. Chem. Soc. Jpn.* **1987**, *60*, 767. (e) Kwon, H. B.; McKee, B. H.; Stille, J. K. *J. Org. Chem.* **1990**, *55*, 3114. For reaction of silicon derivatives see: (f) Hatanaka, Y.; Hiyama, T. *J. Org. Chem.* **1988**, *53*, 918. For reaction of aluminum derivatives see: (g) Baba, S.; Negishi, E. *J. Am. Chem. Soc.* **1976**, *98*, 6729. For reaction of magnesium derivatives see: (h) Dang, H. P.; Linstrumelle, G. *Tetrahedron Lett.* **1978**, *19*, 191. For reaction of boron derivatives see: (i) Suzuki, A. *Pure Appl. Chem.* **1985**, *57*, 1749.

(3) (a) Cabri, W.; Candiani, I.; Bedeschi, A.; Santi, R. *Tetrahedron Lett.* **1991**, *32*, 1753. (b) Cabri, W.; Candiani, I.; Bedeschi, A.; Santi, R. *J. Org. Chem.* **1990**, *55*, 3654. (c) Cabri, W.; Candiani, I.; Bedeschi, A.; Penco, S.; Santi, R. *J. Org. Chem.* **1992**, *57*, 1481.

(4) Collman, J. P., Hegedus, L. S.; Norton, J. R.; Finke, R. G. *Principles and Applications of Organotransition Metal Chemistry*, 2nd ed.; University Science Books: Mill Valley, CA, 1987; p 724.

(5) DPPE = 1,2-bis(diphenylphosphino)ethane; DPPP = 1,3-bis(diphenylphosphino)propane; DPPB = 1,4-bis(diphenylphosphino)butane; DPPF = 1,1′-bis(diphenylphosphino)ferrocene.

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Table I. Palladium-Catalyzed Reaction between Olefins 1a–k and 1-Naphthyl Triflate 2. Bidentate Phosphine Ligand Effect[a]

entry	olefin	ligand (L/Pd)[b]	T (°C)	t (h)	4/5[c]	E/Z[c]	product (yield,[d] %)
1	**1a**	DPPP (1.1)	80	1	>99/1		**7** (97)[e]
2	**1a**	DPPF (2)	80	1.5	>99/1		**7** (91)[e]
3	**1b**	DPPP (1.1)	100	1.5	>99/1		**4b** (92)
4	**1b**	DPPF (2)	100	2.5	>99/1		**4b** (60)[f]
5	**1c**	DPPP (1.1)	100	7	99/1		**4c** (87)
6	**1c**	DPPB (2)	100	9	93/7	>99/1	**4c** (68) + **5c** (5)[g]
7	**1d**	DPPP (1.1)	80	2.5	>99/1		**4d** (50)[h]
8	**1d**	DPPF (2)	80	1	>99/1		**4d** (90)
9	**1e**[i]	DPPF (2)	80	1.5	95/5		**4e** (87) + **8** (4)
10	**1f**	DPPP (1.1)	80	3.5	90/10	>99/1	**4f** + **5f** (92)
11	**1g**[j]	DPPP (1.1)	100	6	95/5	78/22	**4l** (81) + **5g** (4)
12	**1h**	DPPP (1.1)	80	3	38/62	>99/1	**4h** (37) + **5h** (60)
13	**1i**[i]	DPPP (1.1)	100	5	62/38	>99/1	**4i** (48) + **5i** (27)[k]
14	**1j**	DPPP (1.1)	80	1.5	<1/99	>99/1	**5j** (96)
15	**1j**	DPPE (2)	80	10	<1/99	>99/1	**5j** (92)
16	**1k**	DPPP (1.1)	100	28	<1/99	60/40	**5k** (41) + **9** (55)
17	**1k**	DPPF (2)	100	26	<1/99	60/40	**5k** (50)[l]

[a] Reactions were run under an argon atmosphere with 1 equiv of **2**, 2 equiv of the olefin, 1.1 equiv of Et_3N, and 2.5 mol % of $Pd(OAc)_2$ in DMF. [b] Molar ratio between $Pd(OAc)_2$ and the ligand. [c] Determined by GC and ^1H NMR of the crude. [d] Isolated yield. [e] Yield of the corresponding methyl ketone **7** obtained after acidic workup and purification. [f] 32% of **6**. [g] 16% of **6**. [h] 56% conversion. [i] 5 equiv of olefin was used. [j] 10 equiv of **1g** and 2 equiv of Et_3N were used. [k] 15% of **6**. [l] 37% of **6**.

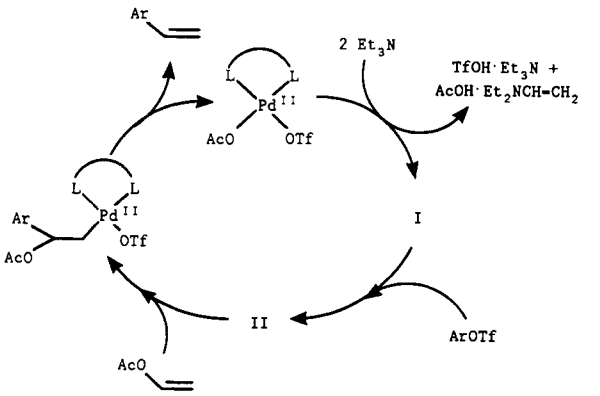
The results of the reaction between 1-naphthyl triflate (**2**) and olefins **1a–k** in DMF are collected in Table I.

The α-regioselectivities observed with the π-systems **1a–i** were superior to the ones previously reported (entries 1–12).[1,7-10] In particular, almost complete selectivity for the α-arylated products was observed, in the limits of ^1H NMR and capillary GC, for butyl vinyl ether (**1a**),[1e,3] enamides **1b,c**,[1,7] and allyl alcohols **1d–e**[1,8] (entries 1–8). Furthermore, the corresponding α-arylated products **7**, **4b–e** were isolated in good yields.

Vinyl pyrrolidinone (**1b**) was reported by Heck to give a 40/60 α/β ratio.[7] On the contrary, by using DPPP, DPPF, or DPPB as palladium ligands, an almost complete α-regioselectivity was observed in the arylations of **1b** and **1c** by **2** (entries 3–6).

It is worth noting that the arylation of allyl alcohols **1d–e** has been the subject of several papers, and recently Jeffery reported a β-regioselective arylation of allyl alcohols with α/β ratio up to 0/100.[8b-c] We have developed a complementary procedure; in fact, allyl alcohol **1d** gave complete α-regioselectivity when DPPP was the ligand. After 2.5 h the reaction stopped (entry 7) because of the capability of the DPPP-containing catalyst to generate a stable π-allyl system.[11] However, with a simple modification of the reaction conditions, namely the use of DPPF as palladium ligand, it was possible to achieve complete α-regioselectivity and conversion (entry 8). The reaction conditions were successfully extended to alcohol **1e** (entry 9).

Scheme III



Homoallyl alcohol **1f** was reported to give preferentially β attack.[9] On the contrary, under our reaction conditions, a 90/10 α/β mixture of products was isolated (entry 10).

The reaction of vinyl acetate **1g** is of synthetic interest;[10] in fact, the use of this olefin resulted in a cheap synthetic equivalent of ethylene, affording via the α-attack pathway 1-naphthyl ethylene (**4l**) (entry 11). In this case the addition of 2 equiv of Et_3N was necessary for the catalyst recycling (Scheme III).

Styrene (**1h**)[1] and vinyl succinimide (**1i**)[7] were reported to give selectively the β-arylated products. By using triflate as leaving group and DPPP as ligand, mixtures of products **4h/5h** (38/62) and **4i/5i** (62/38) were, respectively, isolated (entries 12 and 13).

Methyl acrylate (**1j**) and acrylonitrile (**1k**) gave the usual β-attack products[1] (entries 14–17), but the DPPP-containing catalyst afforded, in the arylation of **1k**, 55% yield of 3-(1-naphthyl)propionitrile (**9**) (entry 16). On the other hand, by using DPPF as ligand considerable quantities of naphthalene (**6**) were isolated (entry 17). Triethylamine was the hydride source in both these side reactions.[12]

With a few exceptions DPPP gave the best performances in terms of regioselectivity, reaction rate, and the product yields; furthermore, only a slight excess of ligand was

(6) Heck-type reactions: (a) Reference 3. (b) Cabri, W.; Candiani, I.; DeBernardinis, S.; Francalanci, F.; Penco, S.; Santi, R. *J. Org. Chem.* **1991**, *56*, 5796. Palladium-catalyzed reduction of aryl sulfonates: (c) Cabri, W.; DeBernardinis, S.; Francalanci, F.; Penco, S.; Santi, R. *J. Org. Chem.* **1990**, *55*, 350. (d) Cabri, W.; DeBernardinis, S.; Francalanci, F.; Penco, S. *J. Chem. Soc., Perkin Trans. 1* **1990**, 428.

(7) Ziegler, C. B.; Heck, R. F. *J. Org. Chem.* **1978**, *43*, 2949.

(8) For recent examples of palladium-catalyzed arylation of allyl alcohols see: (a) Benhaddu, R.; Czernecki, S.; Ville, G. *J. Chem. Soc., Chem. Commun.* **1988**, 247. (b) Jeffery, T. *J. Chem. Soc., Chem. Commun.* **1991**, 324. (c) Jeffery, T. *Tetrahedron Lett.* **1991**, *32*, 2121.

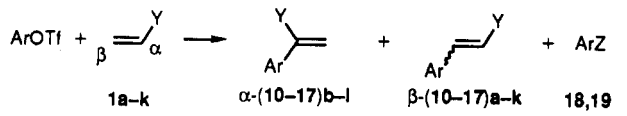
(9) (a) Melpolder, J. B.; Heck, R. F. *J. Org. Chem.* **1976**, *41*, 265. (b) Chalk, A. J.; Magennis, S. A. *J. Org. Chem.* **1976**, *41*, 1206. (c) Larock, R. C.; Leung, W.-Y.; Stolz-Dunn, S. *Tetrahedron Lett.* **1989**, *30*, 6629.

(10) The use of vinyl acetate (**1g**) in Heck-type reactions gave mixture of products.[1] The only exceptions were the reaction of iodouraciles (Arai, I.; Daves, G. D., Jr. *J. Heterocycl. Chem.* **1978**, *15*, 951 (complete α-regioselectivity)) and the reaction of vinyl triflates (Ciattini, P. G.; Morera, E.; Ortar, G. *Tetrahedron Lett.* **1991**, *32*, 1579 (complete β-regioselectivity).

(11) For direct generation of a palladium π-allyl system from allyl alcohols see: (a) Yamamoto, T.; Akimoto, M.; Saito, O.; Yamamoto, A. *Organometallics* **1986**, *5*, 1559. (b) Bergbreiter, D. E.; Weatherford, D. A. *J. Chem. Soc., Chem. Commun.* **1989**, 883. (c) Zair, T.; Santelli-Rouvier, C.; Santelli, M. *Tetrahedron Lett.* **1991**, *32*, 4501.

(12) For examples of palladium catalyzed reactions using as hydride source trialkylamine see: (a) Reference 6b. (b) Saá, J. M.; Dopico, M.; Martorell, G.; Garcia-Raso, A. *J. Org. Chem.* **1990**, *55*, 991. (c) Stokker, G. E. *Tetrahedron Lett.* **1987**, *28*, 3179.

Table II. Palladium-Catalyzed Arylation of Olefins 1a–j by Aryl Triflates. Aryl Substituent Effects[a]



	Ar		Ar		ArZ
10	4-CH_3Ph-	14	4-CH_3OPh-	18	4-CH_3PhCOCH$_3$
11	3-CH_3Ph-	15	Ph-	19	4-CH_3OPhCH$_2$CH$_2$COCH$_3$
12	4-CNPh-	16	3-NO_2Ph-		
13	3-CH_3COPh-	17	3-CNPh-		

entry	Ar	olefin	T (°C)	t (h)	α/β[b]	E/Z[b]	product (yield,[c] %)
1	10	1a	80	5	>99/1		18 (91)[d]
2	11	1b	100	2.5	>99/1		α-11b (81)
3	12	1c[e]	100	15	>99/1		α-12c (82)
4	13	1d[f]	80	3.5	>99/1		α-13d (75)
5	14	1e[e,g]	80	24	96/4		α-14e (83) + 19 (2)
6	15	1f	100	3.5	72/28	>99/1	α-15f (67) + β-15f (23)
7	16	1g[h]	100	12	>99/1		α-16l (80)
8	15	1h	80	4	43/57	>99/1	α-15h (37) + β-15h (55)
9	17	1i[e]	100	15	26/74	>99/1	α-17i (25) + β-17i (71)
10	14	1j	100	48	<99/1	>99/1	β-14j (84)

[a] Reactions were run under an argon atmosphere with 1 equiv of triflate, 2 equiv of the olefin, 1.1 equiv of Et_3N, 2.75 mol % of DPPP, and 2.5 mol % of $Pd(OAc)_2$ in DMF. [b] Determined by GC and ^1H NMR of the crude. [c] Isolated yield. [d] Yield determined after acidic workup and purification. [e] 5 equiv of olefin was used. [f] 5 mol % of DPPF was added as ligand. [g] The reaction was carried out in the presence of Pd(OAc) 5 mol % and DPPF 5.5 mol %. 90% conversion. [h] 10 equiv of 1g and 2 equiv of Et_3N were used.

necessary to generate a stable and effective catalyst.

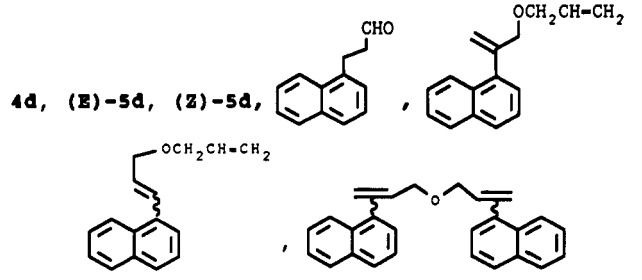
Several functionalities were compatible with the reaction conditions, and the regioselectivity was almost independent from the aryl substituents (Table II).

The results reported in Table III stressed the importance of the leaving group on the aryl moiety. In fact, the effectiveness of the DPPP-containing catalyst decreased, in terms of regioselectivity control and reaction rate, when 1-naphthyl iodide **3** was reacted with olefins **1a–c** and **1h,i** (entries 1–5). Allyl alcohols **1d**, **1e** and homoallyl alcohol **1f** afforded complex final reaction mixtures,[13] and the determination of the α/β ratios was not possible. The catalyst performances were good only with electron-poor olefins **1i–k** (entries 6–8).

Discussion

The results obtained with 1-naphthyl iodide **3** are in agreement with Heck work on the arylation of olefins by

(13) The reaction of **3** with allyl alcohols afforded a bad mixture of



products.

The reaction of **3** with homoallyl alcohol **1f** afforded a complex inseparable mixture of products.

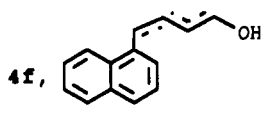


Table III. $Pd(OAc)_2$/DPPP-Catalyzed Arylation of Olefins 1a–c,g–k by 1-Naphthyl Iodide 3[a]

entry	olefin	T (°C)	t (h)	4/5[b]	E/Z[b]	product (yield,[c] %)
1	1a	80	24[d]	69/31	66/34	7 (53) + 5a (22)[e]
2	1b	100	16	68/32	>99/1	4b (62) + 5b (27)
3	1c	100	24	72/28	>99/1	4c (59) + 5c (22)
4	1g[f]	100	24[g]	81/19	80/20	4l (62) + 5g (14)
5	1h	80	24	10/90	>99/1	4h (8) + 5h (83)
6	1i[h]	100	5	6/94	>99/1	4i (4) + 5i (74)
7	1j	80	1	<1/99	>99/1	5j (93)
8	1k[h]	100	3	<1/99	68/32	5k (85)

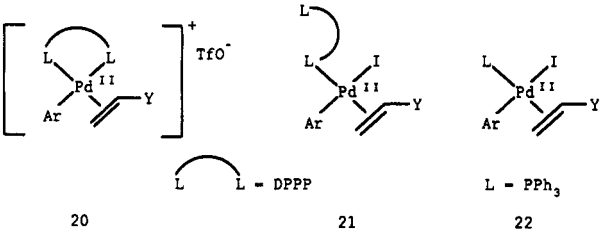
[a] Reactions were run under an argon atmosphere with 1 equiv of **3**, 2 equiv of the olefin, 1.1 equiv of Et_3N, 2.75 mol % of DPPP, and 2.5 mol % of $Pd(OAc)_2$ in DMF. [b] Determined by GC and ^1H NMR of the crude. [c] Isolated yield. [d] Yield determined after acidic workup and purification. [e] 88% conversion. [f] 10 equiv of **1g** and 2 equiv of Et_3N were used. [g] 85% conversion. [h] 10% of **6** was present after 24 h. [h] 5 equiv of olefin was used.

aryl iodides and bromides: "Chelating diphosphines...in general do not produce useful catalyst."[1d]

This observation is not valid when trifluoromethanesulfonate is used as leaving group.[14] The reaction rates and the regioselectivities observed are function of the leaving group present on the aromatic ring. The modifications of the catalyst performances indicate that a different coordination–insertion pathway (b, Scheme I) is allowed as a function of the counterion X present in the oxidative addition complex II.

We[3c,6b] and Hayashi[15] have already proposed two possible pathways for the coordination–insertion step in Heck-type reactions. The results described in this paper are easily explained on the basis of the same mechanistic hypothesis.

The regioselectivity of the aromatic ring migration onto the coordinated olefin is due to a balance between electronic and steric factors.



20 21 22

The presence of the triflate anion in the oxidative–addition complex II (X = OTf, Scheme I) allows the coordination of the olefin in the cationic complex **20**.[16] The polarization of the resulting π-system increased with respect to the noncoordinated olefins, and the migration of the aryl moiety is greatly affected by electronic factors. In spite of the fact that steric factors always favor the formation of linear products (β-attack), with olefins **1a–i** a high selectivity for the migration onto the carbon with the lower charge density (α-attack) was observed (Table I entries 1–13, Table II entries 1–9). Similar selectivities were observed by Hegedus and co-workers in the case of

(14) Bidentate phosphines containing catalyst proved to be effective in the arylation of olefins by aryl and aroyl halides when sequestrating agents for halide anions (Tl(I) and Ag(I) salts) were added to the reaction mixture. For an extensive literature account and mechanistic discussion see ref 3c.

(15) Ozawa, F.; Kubo, A.; Hayashi, T. *J. Am. Chem. Soc.* **1991**, *113*, 1417.

(16) Stang described the exceptional lability of the metal–triflate bond in platinum(II) and palladium(II) complexes. See: (a) Stang, P. J.; Kowalski, M. H.; Schiavelli, M. D.; Longford, D. *J. Am. Chem. Soc.* **1989**, *111*, 3347. (b) Stang, P. J.; Kowalski, M. H. *J. Am. Chem. Soc.* **1989**, *111*, 3356. (c) Hinkle, R. J.; Stang, P. J.; Kowalsky, M. H. *J. Org. Chem.* **1990**, *55*, 5033.

Table IV. $Pd(OAc)_2$/2 PPh_3-Catalyzed Arylation of Olefins 1a–c,g–k by 1-Naphthyl Iodide 3[a]

entry	olefin	T (°C)	t (h)	4/5[b]	E/Z[b]	product (yield,[c] %)	6 (yield,[b] %)
1	1a	80	14	76/24	47/53	7 (74) + 5a (23)[d]	
2	1b	100	4.5	64/36	>99/1	4b (54) + 5b (27)	16
3	1c	100	3.5	71/29	>99/1	4c (58) + 5c (21)	16
4	1g[e]	100	3.5	65/35	71/29	4l (59) + 5g (22)	
5	1h	80	4.5	7/93	>99/1	4h (6) + 5h (82)	8
6	1i[f]	100	1.5	5/95	>99/1	4i (5) + 5i (71)	11
7	1j	80	2	<1/99	>99/1	5j (91)	
8	1k[f]	100	0.5	<1/99	69/31	5k (92)	

[a] Reactions were run under an argon atmosphere with 1 equiv of 3, 2 equiv of the olefin, 1.1 equiv of Et_3N, 5.0 mol % of PPh_3, and 2.5 mol % of $Pd(OAc)_2$ in DMF. [b] Determined by GC and ^1H NMR of the crude. [c] Isolated yield. [d] Yield determined after acidic workup and purification. [e] 10 equiv of 1g and 2 equiv of Et_3N were used. [f] 5 equiv of olefin was used.

external nucleophilic attack on palladium(II)-complexed olefins.[17]

With methyl acrylate 1j and acrylonitrile 1k, steric and electronic factors operate toward the same direction, favoring the β-attack with formation of the linear products (Table I entries 14–17, Table II entry 10).

When iodide is the counterion in the oxidative–addition complex II (X = I, Scheme I) the scenario is completely different. In fact, the olefin coordination takes place by dissociation of one of the phosphorous atoms of the bidentate phosphine, generating the neutral complex 21. In this case, the polarization of the π system is lower with respect to the coordination of the olefin in the cationic complex 20 and the influence of electronic factors on the regioselectivity decreases, resulting in the arylations of olefins 1a–i a higher preference for the β-attack (cf. Tables I and III). Again, with 1j and 1k only the β-arylated products 5j and 5k were formed, but in this case the side reactions were suppressed.[6b]

Interestingly, the outcome of the competitive arylation of butyl vinyl ether (1a) and methyl acrylate (1j) catalyzed by $Pd(OAc)_2$/DPPP was dependent on the leaving group present on the aromatic ring, or in other words from the counterion in the oxidative–addition complex II. 1-Naphthyl triflate (2) was more reactive toward the electron-rich olefin 1a; on the contrary, 1-naphthyl iodide (3) was more reactive toward the electron-poor one 1j (eq 1).

$$\mathbf{1a} + \mathbf{1j} + \mathrm{ArX} \xrightarrow[2.\ H^+]{1.\ Pd(OAc)_2/DPPP} \mathbf{7} + \mathbf{5j} \qquad (1)$$

ArX	7/5j ratio
2	72/28
3	3/97

The coordination of an electron-rich olefin (good σ donor) is favored in a cationic complex (20). On the contrary, the π back-donation from the metal to the olefin is higher in a neutral complex (21) than in a cationic one (20), resulting in a favored coordination of the electron-poor olefins 1j (good π acceptor).[6b]

In order to confirm this mechanistic hypothesis, we have carried out the arylation of 1a–c and 1h–k by 3 in the presence of PPh_3 as ligand (Table IV).

The regioselectivities showed in Tables III and IV are similar. This is in agreement with the hypothesis that, with either PPh_3 or DPPP as ligand and iodide as counterion, the coordination of the olefin takes place by ligand dissociation, affording similar neutral palladium(II) complexes 21 and 22. The arylations carried out with $Pd(OAc)_2$/2PPh_3 were faster than those carried out with the DPPP-containing catalyst (cf. Tables III and IV). This outcome is due to the fact that PPh_3 dissociates from the metal center more easily than DPPP,[18] resulting in an acceleration of the overall reaction rate.[19]

Conclusions

Bidentate phosphine ligands generate effective catalysts for palladium-catalyzed arylation of olefins by aryl triflates. The performances of these catalytic systems, in terms of regioselectivity and reaction rates, allow the extension of the synthetic usefulness of the methodology.

Although on the basis of indirect observation,[20] our results point out that the dualistic hypothesis for the coordination–insertion step has a general validity in Heck-type reactions.

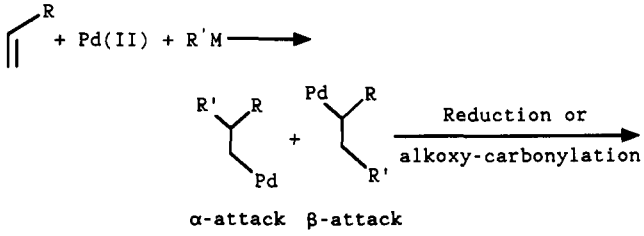
Experimental Section

All compounds were identified and characterized through their 200-MHz ^1H NMR spectra in $CDCl_3$, mass spectra, mp (Kofler apparatus and uncorrected), and bp (bulb-to-bulb distillation conducted with a Büchi Kugelrohr). GC analyses were carried out with a Nordibond OV-1 column (25-m length, i.d. 0.32 mm) and a flame ionization detector.

DMF and Et_3N were distilled over CaH_2 and stored over activated 4A molecular sieves. Aryl triflates[3c] and vinyl succinimide (1i)[21] were prepared by reported procedures. Olefins 1a–h,j–k, 1-naphthyl iodide (3), $Pd(OAc)_2$, PPh_3, DPPE, DPPP, DPPB, and DPPF were Aldrich products and used as received.

Products 4l,[22] 5a,[3b] (E)-5h,[22a] 7,[22] 8,[23] α-15f,[22a] (E)/(Z)-β-15f,[24] α-15h,[22] (E)-β-15h,[22] α-16l,[22] 18,[22,25] and 19[22] are known com-

(17) With N-vinylacetamide, styrene, and other terminal olefins a preference for the α-attack was always observed. See: Hegedus, L. S.; Darlington, W. H. *J. Am. Chem. Soc.* **1980**, *102*, 4980 and references therein.



(18) Tolman, C. A. *Chem. Rev.* **1977**, *77*, 313.

(19) The arylation of vinyl butyl ether by aryl triflates carried out in the presence of PPh_3 take place by dissociation of the phosphine ligand.[3c] However, with triflate as leaving group the reaction rates observed with $Pd(OAc)_2$/2PPh_3 and $Pd(OAc)_2$/DPPP are not comparable because of the fact that the reactions follow different coordination-insertion pathways.

(20) Any attempt to isolate the oxidative–addition complex II, X = OTf, and as neutral ligands monodentate of bidentate phosphines failed (Scheme I).

(21) Bayer, E.; Geckeler, K. *Angew. Chem., Int. Ed. Engl.* **1979**, *18*, 533.

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(23) Mayer, F.; Sieglitz, A. *Chem. Ber.* **1922**, *55*, 1835.

(24) Crombie, L.; Wyvill, R. D. *J. Chem. Soc., Perkin Trans. 1* **1985**, 1983.

pounds, and their structures were determined by comparison of their physical and spectroscopic data with the reported values.

Palladium-Catalyzed Reaction. General Procedure (Table I, Entry 3). To a stirred solution of **2** (1 g, 3.62 mmol) in DMF (10 mL) under an argon atmosphere at rt were sequentially added Et_3N (0.402 g, 0.554 mL, 3.98 mmol), **1b** (0.804 g, 0.773 mL, 7.24 mmol), DPPP (0.044 g, 0.1 mmol), and $Pd(OAc)_2$ (0.0203 g, 0.090 mmol). The reaction was stirred and heated at 100 °C for 1.5 h and then cooled to rt, diluted with CH_2Cl_2 (100 mL), and sequentially washed with 5% HCl (2 × 15 mL) and water until neutrality was achieved. The organic phase was dried (Na_2SO_4) and filtered, and the solvent was removed under reduced pressure. The crude was purified by flash chromatography[26] (hexane/ethyl acetate (7/3) by volume) affording **1-[1-(1-naphthyl)-ethenyl]-2-pyrrolidinone (4b)** (0.790 g, 92%): colorless oil; bp 225–227 °C (2 mmHg); IR (neat) 2980, 2890, 1700, 1630 cm^{-1}; ^1H NMR δ 8.08–7.62 (m, 3 H), 7.65–7.30 (m, 4 H), 5.81 (s, 1 H), 5.14 (s, 1 H), 3.24 (t, J = 7.1 Hz, 2 H), 2.52 (t, J = 7.9 Hz, 2 H), 2.05–1.72 (m, 2 H). Anal. Calcd for $C_{16}H_{15}NO$: C, 80.98; H, 6.37; N, 5.90. Found: C, 81.00; H, 6.38; N, 5.87.

(*E*)-1-[2-(1-Naphthyl)ethenyl]-2-pyrrolidinone [(*E*)-5b]: pale yellow solid; mp 125–127 °C (CH_2Cl_2/hexane); IR ($CHCl_3$) 2990, 1690, 1635 cm^{-1}; ^1H NMR δ 8.15–7.30 (m, 8 H), 6.55 (d, J = 22.6 Hz, 1 H), 3.78 (t, J = 7.1 Hz, 2 H), 2.58 (t, J = 7.9 Hz, 2 H), 2.38–2.05 (m, 2 H). Anal. Calcd for $C_{16}H_{15}NO$: C, 80.98; H, 6.37; N, 5.90. Found: C, 88.95; H, 6.40; N, 5.86.

***N*-Methyl-*N*-[1-(1-naphthyl)ethenyl]acetamide (4c):** waxy solid; bp 198–200 °C (0.2 mmHg); IR (neat) 1660, 1630, 1375 cm^{-1}; ^1H NMR δ 8.33–8.10 (m, 1 H), 7.95–7.80 (m, 2 H), 7.63–7.32 (m, 4 H), 5.50 (s, 1 H), 5.44 (s, 1 H), 3.05 (s, 3 H), 2.19 (s, 3 H). Anal. Calcd for $C_{15}H_{15}NO$: C, 79.97; H, 6.71; N, 6.22. Found: C, 79.99; H, 6.73; N, 6.20.

(*E*)-*N*-Methyl-*N*-[2-(1-naphthyl)ethenyl]acetamide [(*E*)-5c]: pale yellow oil; bp 235–237 °C (0.3 mmHg); IR (neat) 1665, 1630, 1380 cm^{-1}; ^1H NMR δ 8.15–7.36 (m, 7 H), 7.31 (d, J = 13.8 Hz, 1 H), 6.63 (d, J = 13.8 Hz, 1 H), 3.34 (s, 3 H), 2.33 (s, 3 H). Anal. Calcd for $C_{15}H_{15}NO$: C, 79.97; H, 6.71; N, 6.22. Found: C, 79.95; H, 6.69; N, 6.21.

2-(1-Naphthyl)-2-propen-1-ol (4d): colorless oil; bp 211–213 °C (2 mmHg); IR (neat) 3420, 3050, 1650, 1595, 1400 cm^{-1}; ^1H NMR δ 8.10–7.31 (m, 7 H), 5.72–5.66 (m, 1 H), 5.28–5.22 (m, 1 H), 4.48–4.41 (m, 2 H), 1.8 (bs, 1 H). Anal. Calcd for $C_{13}H_{12}O$: C, 84.75; H, 6.57. Found: C, 84.79; H, 6.59.

3-(1-Naphthyl)-3-buten-1-ol (4e): colorless oil; IR (neat) 3350, 3040, 2970, 1400, 900 cm^{-1}; ^1H NMR δ 8.06–7.73 (m, 3 H), 7.53–7.21 (m, 4 H), 5.70 (t, J = 1.6 Hz, 1 H), 5.16 (bs, 1 H), 4.70 (bq, J = 6.5 Hz, 1 H), 1.77 (bs, 1 H), 1.26 (d, J = 6.5 Hz, 3 H). Anal. Calcd for $C_{14}H_{14}O$: C, 84.81; H, 7.12. Found: C, 84.79; H, 7.09.

3-(1-Naphthyl)-3-buten-1-ol (4f) and (*E*)-4-(1-naphthyl)-3-buten-1-ol [(*E*)-5f)]: colorless oil; ^1H NMR δ 8.15–8.06 (m, 1 H), 7.91–7.70 (m, 2 H), 7.60–7.28 (m, 4 H), 7.24 (d, J = 15.6 Hz, 0.1 H), 6.21 (dt, J = 7.14, 15.6 Hz, 0.1 H), 5.47–5.51 (m, 0.9 H), 5.22 (d, J = 2.0 Hz, 0.9 H), 3.81 (t, J = 6.2 Hz, 0.2 H), 3.63 (t, J = 6.5 Hz, 1.8 H), 2.79 (dt, J = 0.8, 6.5 Hz, 1.8 H), 2.65–2.54 (m, 0.2 H); GC–MS **4f** m/e 198 (M^+), 167 (100), 154; **(*E*)-5f** m/e 198 (M^+), 167 (100), 165, 152.

(*E*)-1-(Acetyloxy)-2-(1-naphthyl)ethylene [(*E*)-5g] and (*Z*)-1-(acetyloxy)-2-(1-naphthyl)ethylene [(*Z*)-5g]: colorless oil; ^1H NMR δ 8.08–7.32 (m, 8 H), 7.09 (d, J = 22.5 Hz, 0.78 H, *E* isomer), 6.37 (d, J = 7.3 Hz, 0.22 H, *Z* isomer), 2.21 (s, 2.34 H, *E* isomer), 2.15 (s, 0.66 H, *Z* isomer); GC-MS **(*E*)-5g** m/e 212 (M^+), 170 (100), 141, 115; **(*Z*)-5g** m/e 212 (M^+), 170 (100), 141, 115.

1-(1-Naphthyl)-1-phenylethylene (4h): white solid; mp 59–61 °C (EtOH); IR ($CHCl_3$) 3060, 1590, 1490, 1445 cm^{-1}; ^1H NMR δ 7.90–7.20 (m, 12 H), 5.97 (d, J = 1.5 Hz, 1 H), 5.37 (d, J = 1.5 Hz, 1 H). Anal. Calcd for $C_{18}H_{14}$: C, 93.87; H, 6.13. Found: C, 93.83; H, 6.10.

1-[1-(1-Naphthyl)ethenyl]succinimide (4i): waxy solid; IR ($CHCl_3$) 3040, 2940, 1720, 1365 cm^{-1}; ^1H NMR δ 8.13–8.05 (m, 1 H), 7.88–7.77 (m, 2 H), 7.58–7.36 (m, 4 H), 5.74 (s, 1 H), 5.70 (s, 1 H), 2.71 (s, 4 H). Anal. Calcd for $C_{16}H_{13}NO_2$: C, 76.48; H, 5.21; N, 5.57. Found: C, 76.45; H, 5.23; N, 5.60.

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(*E*)-1-[2-(1-Naphthyl)ethenyl]succinimide [(*E*)-5i]: white solid; mp 162–164 °C (CH_2Cl_2/hexane); IR ($CHCl_3$) 3055, 1710, 1580, 1175 cm^{-1}; ^1H NMR δ 8.41 (d, J = 14.8 Hz, 1 H), 8.14–8.05 (m, 1 H), 7.88–7.74 (m, 2 H), 7.63–7.38 (m, 4 H), 7.16 (d, J = 14.8 Hz, 1 H), 2.79 (s, 4 H). Anal. Calcd for $C_{16}H_{13}NO_2$: C, 76.48; H, 5.21; N, 5.57. Found: C, 76.47; H, 5.21; N, 5.58.

Methyl (*E*)-3-(1-naphthyl)propenoate [(*E*)-5j]: colorless oil; bp 206–208 °C (2 mmHg); IR (neat) 3420, 3050, 1650, 1595, 1400 cm^{-1}; ^1H NMR δ 8.54 (d, J = 15.8 Hz, 1 H), 8.20–7.37 (m, 7 H), 6.53 (d, J = 15.8 Hz, 1 H), 3.86 (s, 3 H). Anal. Calcd for $C_{14}H_{12}O_2$: C, 79.22; H, 5.70. Found: C, 79.20; H, 5.65.

(*E*)-3-(1-Naphthyl)-2-propenonitrile [(*E*)-5k] and (*Z*)-3-(1-naphthyl)-2-propenonitrile [(*Z*)-5k]: pale yellow oil; ^1H NMR δ 8.21 (d, J = 16.4 Hz, 0.6 H), 8.08–7.82 (m, 3 H), 7.67–7.42 (m, 4.4 H), 5.93 (d, J = 16.3 Hz, 0.6 H), 5.69 (d, J = 11.8 Hz, 0.4 H); GC–MS **(*E*)-5k** 179 (M^+, 100), 178, 152, 151; **(*Z*)-5k** 179 (M^+, 100), 178, 152, 151.

3-(1-Naphthyl)propanonitrile (9): white solid; mp 48–50 °C (hexane); IR ($CHCl_3$) 3060, 2940, 2220, 1595, 1505 cm^{-1}; ^1H NMR δ 7.96–7.78 (m, 3 H), 7.61–6.37 (m, 4 H), 3.41 (t, J = 7.5 Hz, 2 H), 2.73 (t, J = 7.5 Hz, 2 H). Anal. Calcd for $C_{13}H_{11}N$: C, 86.15; H, 6.12; N, 7.73. Found: C, 86.18; H, 6.14; N, 7.70.

1-[1-(3-Methylphenyl)ethenyl]-2-pyrrolidinone (α-11b): colorless oil; bp 195–198 °C (0.3 mmHg); IR (neat) 2980, 1710, 1400, 1325 cm^{-1}; ^1H NMR δ 7.40–7.06 (m, 4 H), 5.36 (s, 1 H), 5.26 (s, 1 H), 3.52 (t, J = 7.0 Hz, 2 H), 2.55 (t, J = 8.1 Hz, 2 H), 2.33 (s, 3 H), 2.18–2.00 (m, 2 H). Anal. Calcd for $C_{13}H_{15}NO$: C, 77.58; H, 7.51; N, 6.96. Found: C, 77.54; H, 7.50; N, 6.90.

***N*-Methyl-*N*-[1-(4-cyanophenyl)ethenyl]acetamide (α-12c):** white solid; mp 117–119 °C (AcOEt); IR (Nujol) 2225, 1655, 1630, 1460 cm^{-1}; ^1H NMR δ 7.67 (d, J = 8.5 Hz, 2 H), 7.49 (d, J = 8.5 Hz, 2 H), 5.81 (s, 1 H), 5.39 (s, 1 H), 3.06 (s, 3 H), 1.98 (s, 3 H). Anal. Calcd for $C_{12}H_{12}N_2O$: C, 71.98; H, 6.04; N, 13.99. Found: C, 72.00; H, 6.01; N, 13.99.

2-(3-Acetylphenyl)-2-propen-1-ol (α-13d): colorless oil; bp 226–228 °C (0.8 mmHg); IR (neat) 3400, 2960, 1670, 1420, 1355 cm^{-1}; ^1H NMR δ 8.03–7.98 (m, 1 H), 7.90–7.80 (m, 1 H), 7.67–7.61 m, 1 H), 7.48–7.37 (m, 1 H), 5.51 (bs, 1 H), 5.41 (bs, 1 H), 4.56 (bs, 2 H), 2.60 (s, 3 H), 1.65 (bs, 1 H). Anal. Calcd for $C_{11}H_{12}O_2$: C, 74.98; H, 6.86. Found: C, 74.95; H, 6.90.

3-(4-Methoxylphenyl)-3-buten-2-ol (α-14e): colorless oil; bp 155–158 °C (0.3 mmHg); IR (neat) 3490, 2980, 1605, 1510 cm^{-1}; ^1H NMR δ 7.38–7.28 (m, 2 H), 6.90–6.81 (m, 2 H), 5.27 (t, J = 1.3 Hz, 1 H), 5.21 (s, 1 H), 4.86–4.70 (m, 1 H), 3.80 (s, 3 H), 1.68 (bd, J = 4.0 Hz, 1 H), 1.31 (d, J = 6.3 Hz, 3 H). Anal. Calcd for $C_{11}H_{14}O$: C, 81.44; H, 8.70. Found: C, 81.40; H, 8.74.

1-[1-(3-Cyanophenyl)ethenyl]succinimide (α-17i): white solid; mp 146–148 °C (AcOEt/hexane); IR ($CHCl_3$) 3035, 2230, 1725, 1370 cm^{-1}; ^1H NMR δ 7.68–7.42 (m, 4 H), 5.99 (d, J = 1.5 Hz, 1 H), 5.46 (d, J = 1.5 Hz, 1 H), 2.93 (s, 4 H). Anal. Calcd for $C_{13}H_{10}N_2O_2$: C, 69.02; H, 4.45; N, 12.38. Found: C, 68.99; H, 4.49; N, 12.32.

(*E*)-2-[1-(3-Cyanophenyl)ethenyl]succinimide [(*E*)-β-17i]: white solid; mp 176–178 °C (CH_2Cl_2/hexane); IR ($CHCl_3$) 3030, 2230, 1715, 1380 cm^{-1}; ^1H NMR δ 7.73–7.38 (m, 5 H), 7.23 (d, J = 15.2 Hz, 1 H), 2.83 (s, 4 H). Anal. Calcd for $C_{13}H_{10}N_2O_2$: C, 69.02; H, 4.45; N, 12.38. Found: C, 69.00; H, 4.47; N, 12.35.

Methyl 3-(4-methoxyphenyl)propenoate (β-14j): white solid; mp 87–88 °C (hexane); IR (Nujol) 1720, 1640, 1610, 1580, 1520 cm^{-1}; ^1H NMR δ 7.63 (d, J = 16.0 Hz, 1 H), 7.50–7.39 (m, 2 H), 6.91–6.83 (m, 2 H), 6.29 (d, J = 16.0 Hz, 1 H), 3.81 (s, 3 H), 3.77 (s, 3 H). Anal. Calcd for $C_{11}H_{12}O_3$: C, 68.74; H, 6.29. Found: C, 68.70; H, 6.34.

The competitive arylations of eq 1 were carried out under the same experimental procedure described above in the presence of 5 equiv of **1a** and 5 equiv of **1j**. The product ratios were determined, after acidic workup, by ^1H NMR.

Registry No. **1a**, 111-34-2; **1b**, 88-12-0; **1c**, 3195-78-6; **1d**, 107-18-6; **1e**, 598-32-3; **1f**, 627-27-0; **1g**, 108-05-4; **1h**, 100-42-5; **1i**, 2372-96-5; **1j**, 96-33-3; **1k**, 107-13-1; **2**, 99747-74-7; **3**, 90-14-2; **4b**, 141171-87-1; **4c**, 141171-88-2; **4d**, 33244-71-2; **4e**, 141171-89-3; **4f**, 141171-90-6; **4h**, 28358-65-8; **4i**, 141171-91-7; **4l**, 826-74-4; **(*E*)-5a**, 127087-64-3; **(*Z*)-5a**, 127087-65-4; **(*E*)-5b**, 141171-93-9; **5c**, 141171-92-8; **(*E*)-5f**, 141171-94-0; **(*E*)-5g**, 141171-95-1; **(*Z*)-5g**, 141171-96-2; **(*E*)-5h**, 2840-87-1; **(*E*)-5i**, 141171-97-3; **(*E*)-5j**,

22837-81-6; (Z)-5k, 141171-98-4; (E)-5k, 93863-65-1; 8, 3506-84-1; 9, 70067-70-8; α11b, 141171-99-5; α12c, 141172-00-1; α13d, 141172-01-2; α14e, 141172-02-3; (E)-β14j, 3901-07-3; α15f, 3174-83-2; (E)-β15f, 770-36-5; α15h, 530-48-3; (E)-β15h, 103-30-0; α16l, 586-39-0; α17i, 141172-03-4; (E)-β17i, 141172-04-5; 18, 122-00-9; 19, 104-20-1; DPPF, 12150-46-8; DPPP, 6737-42-4; DPPB, 7688-25-7; DPPE, 1663-45-2; $CH_3CO_2H \cdot {}^1/_2Pd(II)$, 3375-31-3; 4-$CNC_6H_4OSO_2CF_3$, 66107-32-2; 3-$AcC_6H_4OSO_2CF_3$, 138313-22-1; 4-$MeOC_6H_4OSO_2CF_3$, 66107-29-7; $PhOSO_2CF_3$, 17763-67-6; 3-$NO_2C_6H_4OSO_2CF_3$, 32578-25-9; 3-$CNC_6H_4OSO_2CF_3$, 66152-74-7; 4-$MeC_6H_4OSO_2CF_3$, 29540-83-8; 3-$M3C_6H_4OSO_2CF_3$, 32578-31-7; Ph_3P, 603-35-0.

Supplementary Material Available: Complete characterization of compounds (E)-5h, 8, and α15f (1 page). Ordering information is given on any current masthead page.

Asymmetric Deprotonation and Complexation Reactions Mediated by Chiral Ketals as a Route to Ortho-Disubstituted (η^6-Arene)$Cr(CO)_3$ Complexes

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A series of chiral ketals derived from an aryl ketone or aldehyde and one of several C_2-symmetrical diols were converted to their corresponding (η^6-arene)$Cr(CO)_3$ complexes. The resultant 1,3-dioxolanes were trans substituted at C-4 and C-5 by groups CH_2X, where X = H (1), OCH_3 (2), or $N(CH_3)_2$ (3). Ortho deprotonation was attempted on complexes 1–3 using *tert*-butyllithium in THF solution to afford the corresponding lithio derivatives, which were treated with a variety of electrophiles ($MeOSO_2F$, TMSCl, $Ph_2C(O)$, Ph_2PCl). Although 1 gave a complex mixture of products, complexes 2 and 3 afforded good yields of disubstituted complexes (with the exception that the lithiated derivative of 3 did not undergo methylation when treated with $MeOSO_2F$). The stereoselectivity of the reactions was determined by NMR spectroscopy and found to be in the range of 3:1 for 2 and >9:1 for 3. The sense of diastereoselection were identified by chemical correlations (for compounds derived from 2) and by circular dichroism spectroscopy. Poor diastereoselection was obtained when this protocol was performed on the corresponding acetal ultimately derived from benzaldehyde and *N,N,N',N'*-tetramethyl-1,4-diamino-2,3-butanediol. In addition, a related series of ortho-disubstituted arenes bearing chiral ketal or acetal substituents in the benzylic position were subjected to complexation reactions with (naphthalene)$Cr(CO)_3$ in dibutyl ether. The best diastereoselectivity observed with this methodology was 48%, obtained with the acetal derived from *o*-tolualdehyde and *N,N,N',N'*-tetramethyltartramide.

Chromium arene complexes are valuable because they provide templates for the stereoselective elaboration of side chains and significantly modify the chemical reactivity of the attached arene.[1] The former results from the size of the chromium ligand and the tendency of side chains to adopt particular reactive conformations, whereas the electronic properties of the chromium facilitate either nucleophilic or electrophilic processes at the arene itself (mediated by deprotonation by or addition of organolithium reagents). A number of groups have established the particular utility of optically active η^6-arene chromium complexes for a variety of synthetic application.[2]

A bottleneck in the utilization of this chemistry by synthetic chemists has been the need for improved access to chiral complexes in optically active form. Traditionally, such materials have been obtained using resolution and recrystallization techniques;[2] recently reported variations on this theme include the kinetic resolution of η^6-arene chromium complexes bearing carbonyl-containing side chains using microbial techniques[3] or diastereomeric imine formation reactions.[4] More recently, diastereoselective deprotonation reactions of η^6-arene chromium complexes containing a chiral side chain have been utilized as a route to complexes having an element of planar dissymmetry.[5] These methods have ample precedent in ferrocene chemistry.[6] A complementary approach involves the stereoselective complexation of ortho-disubstituted benzene derivatives having a stereogenic center on one of the side chains; precomplexation with the chromium donor results in the diastereoselective delivery of the $Cr(CO)_3$ group to one of the diastereotopic faces of the arene unit.[1c,7] We have shown that the deprotonation/alkylation method can result in the formation of the opposite diastereomeric complex obtained in the complexation method.[5c]

These complementary methods are limited to substrates containing side chains which (1) are good promoters of ortho lithiation reactions or (2) effectively complex with chromium tricarbonyl donors and afford useful levels of selectivity in the arene complexation reactions. Additionally, (3) units employed in such methods must be nonreactive themselves to highly basic and nucleophilic organolithium species. It is also desirable that the aromatic

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