culated. It appears therefore from this and previous work[1] that both the force fields which have been proposed for alkyl radicals generally underestimate their strain energies, perhaps by even more than our results suggest. Kruppa and Beauchamp have recently proposed for 1-adamantyl, on the basis of PES studies,[9] a value of 3.7 kcal mol^{-1}, as compared to our value of 2.4 kcal mol^{-1} and calculated values of 2.5 and 0.9 kcal mol^{-1} according to the Allinger[3] and Beckhaus[4] force fields, respectively. Bridgehead radicals are apparently more rigid than current force fields, which include a soft out-of-plane bending energy parameter, would imply.

(9) Kruppa, G. H.; Beauchamp, J. L. *J. Am. Chem. Soc.* **1986**, *108*, 2162.

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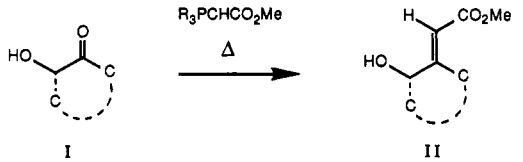
The Stereoselective Synthesis of Acyclic and Exocyclic Trisubstituted Olefins via a Hydroxyl-Directed Wittig Reaction

Summary: Both acyclic and cyclic α-hydroxy ketones undergo an accelerated Wittig reaction with stabilized phosphonium ylides to give *E*-trisubstituted olefins in moderate to good chemical yield.

Sir: The stereocontrolled assembly of tri- and tetrasubstituted olefins—particularly exocyclic ones—is a general problem that continues to attract attention.[1] One impetus for this activity is the incorporation of such moieties in the structures of a variety of interesting natural (and unnatural) products.[2] However there remains a need to develop methodology that is both general and tolerant of sensitive functionality and/or chiral centers which may also be present in such target molecules.

We now wish to report on our observation that both acyclic and exocyclic α-hydroxy ketones such as I undergo an accelerated Wittig reaction with stabilized phosphonium ylides to give the (*E*)-alkenes II selectively in moderate to good chemical yield.[3,4] This simple procedure offers a distinct advantage over related ketone olefination reactions in terms of both mildness and flexibility. A previously unrecognized directing effect of the neighboring hydroxyl group is proposed to account for the enhanced rate and *E* selectivity.[5]



I II

As may be seen from our tabulated results, this reaction has been successfully applied to 3-hydroxy-2-butanone (**1a**), 3-hydroxy-3-methyl-2-butanone (**3a**), 1-hydroxy-2-butanone (**5a**), 2-hydroxycyclohexanone (**12a**), and the highly functionalized pyranone **14a** to give moderate to good yields of the corresponding *E* olefins **2a**, **4a**, **6a**, **13a**, and **15** (entries 1, 2, 7, 10, 18 and 21 Table I).[6,7] In none of these cases was any appreciable amount of the isomeric *Z* olefin (or related material) isolated. It should be noted that compounds **3a** and **5a** reacted much more slowly with Ph_3PCHCO_2Me than the other substrates and required either higher temperatures or the use of a more reactive ylide, n-Bu_3PCHCO_2Me, which was conveniently generated in situ from n-$Bu_3P^+CH_2CO_2Me$ Br^- and Et_3N.[8] The latter procedure proved to be the method of choice for these hindered substrates (compare entries 5–10). On the other hand, Wittig olefination of 1-hydroxy-3-methyl-2-butanone (**7a**) was extremely sluggish and produced product **8a** in only 10% yield under even the best conditions (entries 11–15). In this case a competitive tautomerization occurred and the resulting aldehyde **10** then reacted with ylide to give the disubstituted olefin **11**.[9] The

(1) Recent efforts in this area include: Negishi, E.; Zhang, Y.; Cederbaum, F. E.; Webb, M. B. *J. Org. Chem.* **1986**, *51*, 4082. Corey, E. J.; Siebel, W. L. *Tetrahedron Lett.* **1986**, 905, 909. Shibasaki, M.; Sodeoka, M. *Ibid.* **1985**, 3491. Koreeda, M.; Patel, P. D.; Brown, L. *J. Org. Chem.* **1985**, *50*, 5910. Larson, G. L.; Prieto, J. A.; Hernandez, A. *Tetrahedron Lett.* **1981**, 1575. Srekumar, C.; Darst, K. P.; Still, W. C. *J. Org. Chem.* **1980**, *45*, 4262.

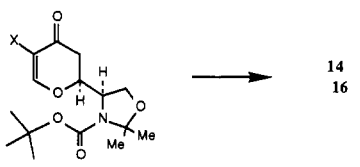
(2) Examples of both natural and unnatural products that contain exocyclic olefins of this type include the following. The bryostatins: Pettit, G. R.; Kamano, Y.; Herald, C. L.; Tozawa, M. *J. Am. Chem. Soc.* **1984**, *106*, 6768 and references therein. Zoapatonol: Levine, S. D.; Adams, R. E.; Chen, R.; Cotton, M. L.; Hirsch, A. F.; Kane, V. V.; Konajia, R. M.; Shaw, C.; Wachter, M. P.; Chin, E.; Huttermann, R.; Ostrowski, P. *Ibid.* **1979**, *101*, 3404. The carbocyclins: Bartman, W.; Beck, G. *Angew. Chem., Int. Ed. Engl.* **1982**, *21*, 751.

(3) In a reaction which complements ours, (triphenylphosphorylidine)ketene reacts with α-hydroxy ketones to give butenolides though the intermediate is in fact an acylated α-hydroxy ketone: Bestmann, H. J. *Angew. Chem., Int. Ed. Engl.* **1976**, *15*, 115. Nickisch, K.; Klose, W.; Bohlmann, F. *Chem. Ber.* **1980**, *113*, 2038. The reaction of stabilized ylides with unprotected α-hydroxy aldehydes is well-known: Barrett, A. G. M.; Broughton, H. B. *J. Org. Chem.* **1984**, *49*, 3673. Schoenenberger, B.; Summermatter, W.; Ganter, C. *Helv. Chim. Acta* **1982**, *65*, 2333. Olejniczak, K.; Frank, R. W. *J. Org. Chem.* **1982**, *47*, 380. See also: Bunce, R. A.; Pierce, J. D. *Tetrahedron Lett.* **1986**, 5583.

(4) It has been reported that a variety of protected α-hydroxy 2-, 3-, and 4-keto sugars react smoothly with Ph_3PCHCO_2Et in boiling CH_3CN to give a single (though not always predictable) geometric isomer in each case: Tulshian, D. B.; Tsang, R.; Fraser-Reid, B. *J. Org. Chem.* **1981**, *46*, 3764. The facility of these reactions as compared to our control experiments is understandable since additional oxygen substituents at the α- or α′-position would be expected to make the carbonyl group more electrophilic via inductive activation.

(5) The effect of nucleophilic groups such as alkoxides which are incorporated into (unstabilized) ylides has been investigated and discussed: Maryanoff, B. E.; Reitz, A. B.; Duhl-Emswiler, B. A. *J. Am. Chem. Soc.* **1985**, *107*, 217. Linderman, R. J.; Meyers, A. I. *Tetrahedron Lett.* **1983**, 3043.

(6) Compounds **1a**, **3a**, and **12a** were purchased from Aldrich Chemical Co.; **5a** and **7a** were prepared from 3-methyl-2-butanone and 2-butanone, respectively, by using a bromination/displacement sequence: Guetle, J. P.; Spassky, N.; Boucherot, D. *Bull. Soc. Chim. Fr.* **1972**, 4217. Gaudry, M.; Marquet, A. *Tetrahedron* **1970**, *26*, 5611. Catch, J. R.; Elliott, D. F.; Hey, D. H.; Jones, E. R. H. *J. Chem. Soc.* **1948**, 272. **14a** and **16** were prepared in one step from the dihydropyrones **19** and **20** via base-catalyzed conjugate addition of MeOH. Both **19** and **20** are known compounds: Garner, P.; Ramakanth, S. *J. Org. Chem.* **1986**, *51*, 2609. The silyl ethers were generally prepared by using the standard method: Corey, E. J.; Venkateswarlu, A. *J. Am. Chem. Soc.* **1972**, *94*, 6190.



19 (X = OAc)
20 (X = H)

(7) Satisfactory IR, ^1H NMR, and HRMS or combustion analyses have been obtained for these substances. The NMR samples for compounds **14–18** were heated to 60 °C to observe conformer averaged spectra.

(8) Cf.: Trippett, S.; Walker, D. M. *J. Chem. Soc.* **1961**, 1266.

(9) Base-(or acid-)catalyzed tautomerization of α-hydroxycarbonyl compounds is a well-known phenomenon in the carbohydrate field. Cf.: Speck, J. C., Jr. *Adv. Carbohydr. Chem.* **1958**, *13*, 63.

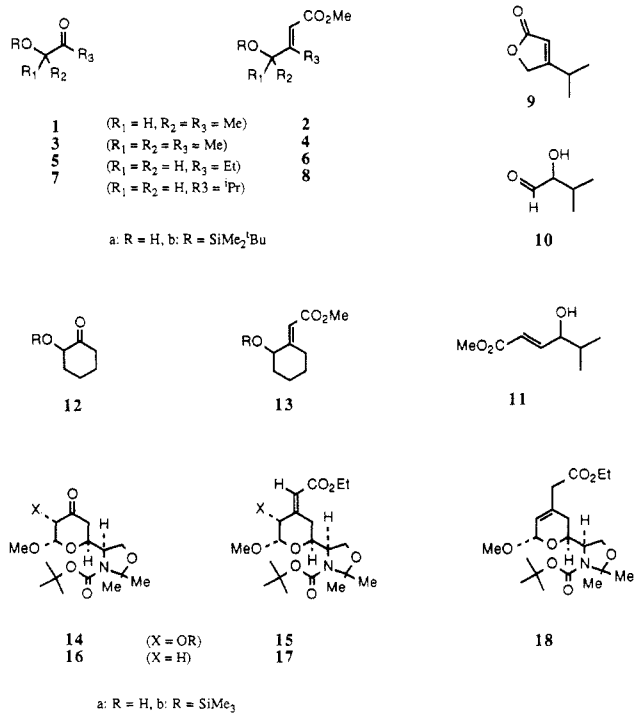
0022-3263/87/1952-2629$01.50/0

Table I. Wittig Olefination of α-Hydroxy Ketones, etc.

entry	substrate	Wittig reagent	reaction conditions[a]	product (yield, %)
1	**1a**[b]	Ph_3PCHCO_2Me	CH_3CN, reflux, 19 h	**2a** (78)
2	**1a**[b]	Ph_3PCHCO_2Me	C_6H_6, reflux, 18 h	**2a** (75)
3	**1a**[b]	Ph_3PCHCO_2Me	CH_3CN, 17 mol % $PhCO_2H$, reflux, 18 h	**2a** (50)[c]
4	**1b**	Ph_3PCHCO_2Me	CH_3CN, reflux, 13 h	**2b** (10)[c,d]
5	**3a**	Ph_3PCHCO_2Me	CH_3CN, reflux, 46 h	**4a** (23)
6	**3a**	Ph_3PCHCO_2Me	toluene, reflux, 31 h	**4a** (24)
7	**3a**	n-Bu_3PCHCO_2Me[e]	C_6H_6, reflux, 52 h	**4a** (46)
8	**5a**	Ph_3PCHCO_2Me	CH_3CN, reflux, 70 h	**6a** (43)
9	**5a**	Ph_3PCHCO_2Me	toluene, reflux, 23 h	**6a** (25)
10	**5a**	n-Bu_3PCHCO_2Me[e]	C_6H_6, reflux, 27 h	**6a** (46)
11	**7a**	Ph_3PCHCO_2Me	CH_3CN, reflux, 28 h	no reaction
12	**7a**	Ph_3PCHCO_2Me	toluene, reflux, 16 h	**8a** (5)[f]
13	**7a**	Ph_3PCHCO_2Me	C_6H_6, reflux, 30 h	**8a** (7)[g]
14	**7a**	n-Bu_3PCHCO_2Me[e]	C_6H_6, reflux, 52 h	**8a** (10)
15	**7a**	$(MeO)_2P(O^-K^+)CHCO_2Me$	DMF, R.T., 8 h	**8a** (10)[c]
16	**7b**	Ph_3PCHCO_2Me	toluene, reflux, 24 h	no reaction
17	**7b**	$(MeO)_2P(O^-K^+)CHCO_2Me$	DMF, R.T., 24 h	**8b** (10)
18	**12a**[b]	Ph_3PCHCO_2Me	CH_3CN, reflux, 5 h	**13a** (94)
19	**12a**[b]	Ph_3PCHCO_2Me	CH_3CN, 1.2 equiv of Et_3N	**13a** (84)
20	**12b**	Ph_3PCHCO_2Me	CH_3CN, reflux, 14 h	**13b** (49)
21	**14a**	Ph_3PCHCO_2Et	CH_3CN, reflux, 8 h	**15a** (74)
22	**14a**	$(EtO)_2P(O^-K^+)CHCO_2Et$	DMF, 0–15 °C, 3 h	**15a** (25)[h]
23	**14b**	Ph_3PCHCO_2Et	toluene, 70 °C, 18 h	no reaction
24	**16**	Ph_3PCHCO_2Et	toluene reflux, 6 h	**17** (trace)[i]
25	**16**	$(EtO)_2P(O^-K^+)CHCO_2Et$	DMF, R.T., 24 h	**17** (36)[j]

[a] Reactions were generally run 0.2–0.3 M in substrate and 0.5–0.8 M in ylide. R.T. = room temperature. [b] Crystalline dimer was used. [c] Substrate was recovered. [d] Inseparable mixture of E/Z isomers. [e] Generated in situ from n-$Bu_3P^+CH_2CO_2Me$ Br^- by the addition of 1 equiv of Et_3N. [f] Products **9** and **11** were also formed in 16% and 28% yields, respectively. [g] Products **9** and **11** were also formed in 1% and 13% yields, respectively. [h] The C(2) epimer of **15a** was also isolated in 8% yield. [i] The major products recovered were **16** and **20**. [j] The isomeric $\Delta^{2,3}$ endocyclic olefin **18** was also produced in 8% yield.

presence of butenolide **9** indicated an overall loss of E selectivity as well. Thus there remain some limitations with hindered substrates that have lower energy pathways available to them.



The reaction seems to be free of significant aprotic solvent effects in that similar results are obtained with either acetonitrile or benzene (entries 1 and 2). This is to be expected if the reaction proceeds via a concerted cycloaddition mechanism to give an oxaphosphetane intermediate directly (vide infra).[10] Attempted use of methanol as a solvent (not shown) resulted in a more complex reaction mixture that contained only marginal amounts of olefinic product. Protection of the free α-hydroxyl group as a silyl ether retarded the rate of reaction considerably (entries 4, 16, 20, and 23) and at least in one case led to erosion of E selectivity. As expected, the absence of any α-oxygen substitution also slowed down the reaction and gave a mixture of olefin isomers as well (entry 24). The alternative Wadsworth–Horner–Emmons modification did proceed at lower temperatures and show E selectivity with free α-hydroxy ketones, but yields were generally poor and the basic nature of this reagent caused additional problems (entries 15, 17, 22, and 25).

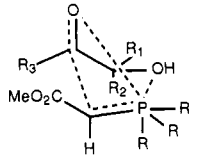
Assignment of olefin geometry in products **2a**, **4a**, **6a**, **8a**, **13a**, and **15a** rests primarily on NMR evidence and correlation with data reported for the known compounds **2a**, **6a**, and **13a**.[11] In general, those allylic protons which are situated "cis" to the ester carbonyl group experience a downfield shift relative to their "trans" counterparts. This is especially apparent with the conformationally locked exocyclic olefin products since an equatorial proton is forced to reside squarely in the deshielding cone of the ester and is thus shifted ca. 1.5 ppm downfield. Furthermore an NOE difference experiment performed on compound **2a** showed a 21% enhancement of the vinyl proton when the carbinol methyl was irradiated, while the reciprocal experiment resulted in a 15% enhancement of the methyl signal. Finally, the workup conditions are such that spontaneous butenolide formation would be expected of any Z olefin formed during the reaction.

While a definitive mechanistic interpretion would at this

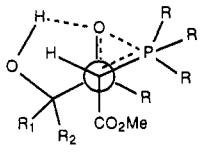
(10) Cf.: Vedejs, E.; Meier, G. P.; Snoble, K. A. J. *J. Am. Chem. Soc.* **1981**, *103*, 2823. Bestmann, H. J. *Pure Appl. Chem.* **1980**, *52*, 771. Giese, B.; Schoch, J.; Ruechardt, C. *Chem. Ber.* **1978**, *111*, 1395. A comprehensive account exploring the mechanism of Wittig reactions in general via analysis of reaction intermediates has just recently appeared: Maryanoff, B. E.; Reitz, A. B.; Mutter, M. S.; Inners, R. R.; Almond, H. R., Jr.; Whittle, R. R.; Olofson, R. A. *J. Am. Chem. Soc.* **1986**, *108*, 7664.

(11) Larcheveque, M.; Perriot, P.; Petit, Y. *Synthesis* **1983**, 297. Yamigawa, S.; Sato, H.; Hoshi, N.; Kosugi, H.; Uda, H. *J. Chem. Soc., Perkin Trans. 1* **1979**, 570.

stage be premature, the following two transition-state models may be useful in rationalizing our results. The first involves initial interaction of an α-hydroxyl group with the phosphorus center of the ylide. This would permit the ylide to add to the carbonyl by way of a *bicyclic* transition state A that minimizes axial substituents as shown. Once C–C bond formation has occurred, syn elimination of Ph_3PO in the usual way would afford the observed *E* olefin. Alternatively, the carbonyl might first be activated by an intramolecular hydrogen bond followed by a concerted cycloaddition of the ylide.[12] In this case the transition-state B (parallel *or* tilted approach of ylide) requires that the large phosphorous ligands approach the conformationally mobile α'-carbon and would explain why the rate of reaction is most sensitive to substitution at this position. As with the previous model, transition-state B leads to a *trans*-oxaphosphetane, which then decomposes to give the observed *E*-olefinic product.



A



B

In light of continued interest in the synthesis and use of functionalized olefins in general, we feel that the described procedure provides a valuable addition to already established methodology. Further studies to delineate the scope and mechanism of this potentially useful hydroxyl-directed Wittig reaction are currently under way.

Acknowledgment. This work was supported by Public Health Service Research Grant GM 35557 from the National Institute of General Medical Sciences and a Case Institute of Technology BRSG Award.

(12) *Intermolecular* acid catalysis of the Wittig reaction between stabilized ylides and ketones is known: Ruecchardt, Ch.; Eichler, S.; Panse, P. *Angew. Chem.* **1963**, *75*, 858.

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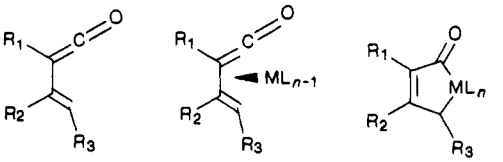
Practical Organic Synthesis with Strained-Ring Molecules. Rhodium-Catalyzed Carbonylation of Cyclopropenyl Esters and Cyclopropenyl Ketones to α-Pyrones and of Vinyl Cyclopropenes to Phenols[1a]

Summary: Cyclopropenyl esters, prepared from alkynes and ethyl diazoacetate via rhodium acetate catalysis, can be converted into cyclopropenyl ketones, which in turn are converted into vinyl cyclopropenes. All three classes of cyclopropenes undergo rhodium-catalyzed carbonylation at 1 atm of CO to provide α-pyrones from the first two classes and phenols from the last.

(1) (a) This work was presented at the 192nd National Meeting of the American Chemical Society, Anaheim, CA, Sept. 7–12, 1986. (b) Fellow of the Alfred P. Sloan Foundation, 1983–1987; Camille and Henry Dreyfus Teacher Scholar, 1986–1991.

Sir: Vinylketenes **1**, generated by the ring opening of cyclobutenones or via eliminations from unsaturated carboxylic acid derivatives, have proven to be useful intermediates in organic synthesis,[2] and during the last few years vinylketene metal complexes **2a–c** have been implicated in reactions of transition-metal carbenes with alkynes which also produce useful organic products.[3]



1 η^4-vinylketene **2a** η^2-vinylketene **2b**

Another procedure known to produce vinylketene–metal complexes is the reaction of cyclopropenes with stoichiometric metal carbonyl reagents.[4] We have developed an interest in synthetically useful metal-catalyzed chemistry of strained-ring organic molecules and were led to consider the possibility of the metal-catalyzed carbonylation of cyclopropenes as a route into vinylketene intermediates with synthetic organic potential. Specifically, we were interested in the metal-catalyzed carbonylation of cyclopropenyl esters and ketones **3**, X = O, and vinylcyclopropenes **3**, X = CHR_4, as a route to α-pyrones and phenols, respectively, as shown in Scheme I. Relevant reactions of cyclopropenes with transition metals can be found in the work of Semmelhack,[5] Binger,[6] Hughes,[7,8] and others.[4,9]

While many cyclopropenes cannot be categorized as attractive starting materials for the synthesis of organic

(2) (a) Smith, L. I.; Hoehn, H. H. *J. Am. Chem. Soc.* **1939**, *61*, 2619; **1941**, *63*, 1181. (b) Druey, J.; Jenny, E. F.; Schenker, K.; Woodward, R. B. *Helv. Chim. Acta* **1962**, *45*, 600. (c) Neuse, E. W.; Green, B. R. *Liebigs Ann. Chem.* **1974**, *1534*. (d) Mayr, H. *Angew. Chem., Int. Ed. Engl.* **1975**, 14, 500. (e) Danheiser, R. L.; Sard, H. *J.* Org. *Chem.* **1980**, *45*, 4810. (f) Danheiser, R. L.; Gee, S. K.; Sard, H. *J. Chem. Soc.* **1982**, *104*, 7670. (g) Huston, R.; Rey, M.; Dreiding, A. S. *Helv. Chim. Acta* **1982**, *65*, 451. (h) Trahonovsky, W. S.; Surber, B. W.; Wilkes, M. C.; Preckel, M. M. *J. Am. Chem. Soc.* **1982**, *104*, 6779. (i) Jackson, D. A.; Rey, M.; Dreiding, A. S. *Tetrahedron Lett.* **1983**, 4817. (j) Danheiser, R. L.; Gee, S. K. *J. Org. Chem.* **1984**, *49*, 1674. (k) Kulkarni, Y.; Burbaum, B. W.; Snider, B. B. *Tetrahedron Lett.* **1985**, 5619. (l) Perri, S. P.; Foland, L. D.; Decker, O. H. W.; Moore, H. *J. Org. Chem.* **1986**, *51*, 3067. (m) Liebeskind, L. S.; Iyer, S.; Jewell, C. F., Jr. *J. Org. Chem.* **1986**, *51*, 3065.

(3) (a) Dötz, K. H. *Angew. Chem., Int. Ed. Engl.* **1975**, *14*, 644. (b) Fischer, H.; Schubert, U.; Hofmann, P.; Kreissl, F. R.; Weiss, K.; Dötz, K. H. *Carbene Complexes*; Verlag Chemie: Weinheim, 1983. (c) Dötz, K. H. *Angew. Chem., Int. Ed. Engl.* **1984**, *23*, 587. (d) Semmelhack, M. F.; Bozell, J. J.; Sato, T.; Wulff, W. D.; Spiess, E.; Sask, A. *J. Am. Chem. Soc.* **1982**, *104*, 5850. (e) Wulff, W. D.; Tang, P. C. *J. Am. Chem. Soc.* **1984**, *106*, 434. (f) Yamashita, A. *J. Am. Chem. Soc.* **1985**, *107*, 5823. (g) Wulff, W. D.; Tang, P. C.; Chan, K. S.; McCallum, J. S.; Yang, D. C.; Gilbertson, S. R. *Tetrahedron* **1985**, *41*, 5813. (h) Tang, P. C.; Wulff, W. D. *J. Am. Chem. Soc.* **1984**, *106*, 1132. (i) Wulff, W. D.; Chan, K. S.; Tang, P. C. *J. Org. Chem.* **1984**, *49*, 2293. (j) Semmelhack, M. F.; Tamura, R.; Schnattner, W.; Springer, *J. J. Am. Chem. Soc.* **1984**, *106*, 5363. (k) Wulff, W. D.; Gilbertson, S. R.; Springer, J. P. *J. Am. Chem. Soc.* **1986**, *108*, 520. (l) Wulff, W. D.; Kaesler, R. W. *Organometallics* **1985**, *4*, 1461. (m) Wulff, W. D.; Kaesler, R. W.; Peterson, G. A.; Tang, P. C. *J. Am. Chem. Soc.* **1985**, *107*, 1060. (n) Dötz, K. H.; Popall, M. J. *Organomet. Chem.* **1985**, *291*, Cl. (o) Dötz, K. H.; Strum, W. *J. Organomet. Chem.* **1985**, *285*, 205. (p) Yamashita, A.; Scahill, T. A.; Toy, A. *Tetrahedron Lett.* **1985**, 1159. (q) Yamashita, A.; Scahill, T. A.; Toy, A. *Tetrahedron Lett.* **1985**, 2969. (r) Katz, J. T.; Sivavec, T. M. *J. Am. Chem. Soc.* **1985**, *107*, 737. (s) Parlier, A.; Rudler, H.; Platzer, N.; Fountanille, M.; Soum, A. *J. Organomet. Chem.* **1985**, *287*, C8. (t) Macomber, D. W. *Organometallics* **1984**, *3*, 1589.

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