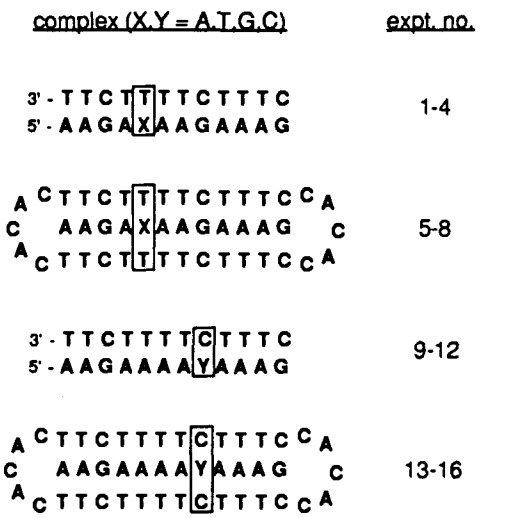


Figure 1. Sequences of the complexes in experiments 1-16. Bases X and Y represent A, G, C, and T. Boxes mark the variable base pair or triad.

Table I. Free Energies of Association ($-\Delta G°_{37}$) and Selectivities of Oligomers **1** and **2** Hybridized to Oligomers with One Variable Base (X or Y)[a]

expt no.	variable base	T_m, °C	$-\Delta G°_{37}$, kcal/mol	selectivity, kcal/mol
duplex				
1	X = A	43.8	10.3	-
2	G	33.8	7.1	3.2
3	C	28.3	5.9	4.4
4	T	31.1	6.4	3.9
circle complex				
5	X = A	62.3	16.4	-
6	G	44.2	10.2	6.2
7	C	39.8	8.8	7.6
8	T	40.8	9.1	7.3
duplex				
9	Y = A	26.2	5.1	5.2
10	G	43.8	10.3	-
11	C	22.2	4.5	5.8
12	T	27.0	5.0	5.3
circle complex				
13	Y = A	39.9	9.0	7.4
14	G	62.3	16.4	-
15	C	41.3	9.3	7.1
16	T	39.6	8.9	7.5

[a] Uncertainty in T_m is estimated as ± 0.5 °C and in $\Delta G°$, ±5%.

(X = A) gives the most favorable complex ($-\Delta G°_{37}$ = 16.4 kcal/mol). The mismatches (X = G, T, C), however, result in a considerably larger loss of binding energy (6.2-7.6 kcal/mol) than for the duplex. Thus, the selectivity of circle **1** for its complement in this case is 6.2-7.6 kcal/mol, compared to 3.2-4.4 kcal/mol for oligomer **2**.

Similarly, experiments 9-12 give the effects of a C-Y mismatch on the duplex. The matched base (Y = G) gives a free energy of duplex association of -10.3 kcal/mol. The mismatches (Y = A, T, C) result in a loss of 5.2-5.8 kcal/mol of binding energy, once again in reasonable agreement with published data.[10] By contrast, the effects of a C-Y-C mismatch in the circle complex are greater (experiments 13-16): the match (Y = G) gives a binding energy of -16.4 kcal/mol, and the mismatches (Y = A, T, C) are less stable by 7.1-7.5 kcal/mol.

Thus, in all cases studied, the circular ligand shows greater selectivity for its correctly matched sequence than does the standard linear oligomer. The selectivity advantage ranges from 1.3-2.2 kcal/mol for the C-Y-(C) series to 3.0-3.4 kcal/mol for the T-X-(T) series. These are large differences, considering they arise from a single base change. For example, in the T-X-(T) series, the circular ligand is more selective than the linear reference oligomer by 1-2 orders of magnitude in binding constant at 37 °C.

There are two factors that may explain this high selectivity. First, because the circular ligand forms close contacts with *two sides* of the central complexed strand, it can, in effect, check the sequence twice for correct matching. A mismatch results in unfavorable interactions in both binding domains of the complex. Secondly, protonation of cytosine within a C+G-C triad may also be a factor in increasing selectivity. This protonation is likely to be favored only when there is a correct match, so that guanine can share the added proton; evidence suggests that the pK_a of cytosine within a triplex is 2-3 units higher than that of deoxycytidine monophosphate.[11,12]

We conclude that circular oligomers can have higher selectivity than can be achieved with standard Watson-Crick complementary oligomers and that they can have higher binding affinities as well. These properties are shared with other known macrocyclic hosts. For example, crown ethers and related cyclic ligands display high selectivity and strong binding for specific guests, as do the "crown nucleotides" in this study. We are currently investigating further the unusual binding properties of circular oligonucleotides and their analogues, and we anticipate that these properties may prove useful in the design of more efficient DNA- and RNA-binding molecules.

Acknowledgment. I thank Dr. D. Turner for helpful discussions.

(11) Callahan, D. E.; Trapane, T. L.; Miller, P. S.; Ts'o, P. O. P.; Kan, L.-S. *Biochemistry* **1991**, *30*, 1650-1655.
(12) D'Souza, D. J.; Kool, E. T., submitted for publication.

Remarkably "Pair"-Selective and Regioselective Carbon-Carbon Bond Forming Reaction of Zirconacyclopentane Derivatives with Grignard Reagents

Tamotsu Takahashi,* Takashi Seki,[1a] Yu Nitto, and Masahiko Saburi

Department of Industrial Chemistry
The University of Tokyo, Tokyo 113, Japan

Christophe J. Rousset[1b] and Ei-ichi Negishi*

Department of Chemistry, Purdue University
West Lafayette, Indiana 47907

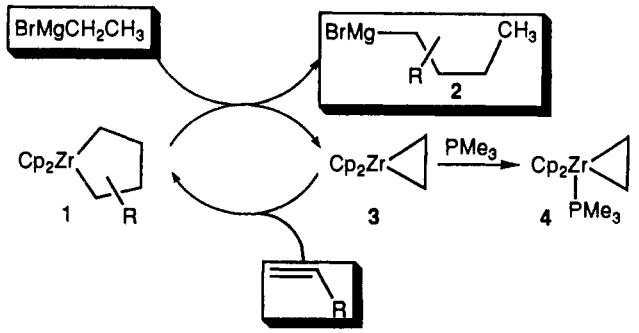
Received July 30, 1990

We report herein (i) "pair"-selective and regioselective formation of 3-alkyl- or 2-aryl-1-zirconacyclopentanes (**1**) via ethyl-alkene coupling reactions[2] of zirconocene-alkene complexes,[3] (ii) clean and regioselective transfer of the substituted tetramethylene groups of **1** from Zr to Mg to produce **2**, and (iii) formation of **3** as the byproduct, which has been identified as **4**. We further report that

(1) (a) Visiting Research Associate, Purdue University (1990). (b) D. Ross Fellow, Purdue University (1988-1990).
(2) (a) Swanson, D. R.; Rousset, C. J.; Negishi, E.; Takahashi, T.; Seki, T.; Saburi, M.; Uchida, Y. *J. Org. Chem.* **1989**, *54*, 3521. (b) Rousset, C. J.; Swanson, D. R.; Lamaty, F.; Negishi, E. *Tetrahedron Lett.* **1989**, *30*, 5105. (c) Nugent, W. A.; Taber, D. F. *J. Am. Chem. Soc.* **1989**, *111*, 6435. (d) Takahashi, T.; Fujimori, T.; Seki, T.; Saburi, M.; Uchida, Y.; Rousset, C. J.; Negishi, E. *J. Chem. Soc., Chem. Commun.* **1990**, 182.
(3) (a) Negishi, E.; Cederbaum, F. E.; Takahashi, T. *Tetrahedron Lett.* **1986**, *27*, 2829. (b) Takahashi, T.; Swanson, D. R.; Negishi, E. *Chem. Lett.* **1987**, 623. (c) Buchwald, S. L.; Watson, B. T.; Huffman, J. C. *J. Am. Chem. Soc.* **1987**, *109*, 2544. (d) Alt, H. G.; Denner, C. E.; Thewalt, U.; Rausch, M. D. *J. Organomet. Chem.* **1988**, *356*, C85. (e) Takahashi, T.; Murakami, M.; Kunishige, M.; Saburi, M.; Uchida, Y.; Kozawa, K.; Uchida, T.; Swanson, D. R.; Negishi, E. *Chem. Lett.* **1989**, 761. (f) Negishi, E.; Holmes, S. J.; Tour, J. M.; Miller, J. A.; Cederbaum, F. E.; Swanson, D. R.; Takahashi, T. *J. Am. Chem. Soc.* **1989**, *111*, 3336. (g) Takahashi, T.; Tamura, M.; Saburi, M.; Uchida, Y.; Negishi, E. *J. Chem. Soc., Chem. Commun.* **1989**, 852. (h) Binger, P.; Muller, P.; Benn, R.; Rufinske, A.; Gabor, B.; Kruger, C.; Bitz, P. *Chem. Ber.* **1989**, *122*, 1035. (i) Negishi, E.; Swanson, D. R.; Takahashi, T. *J. Chem. Soc., Chem. Commun.* **1990**, 1254. (j) Takahashi, T.; Nitto, Y.; Seki, T.; Saburi, M.; Negishi, E. *Chem. Lett.* **1990**, 2259.

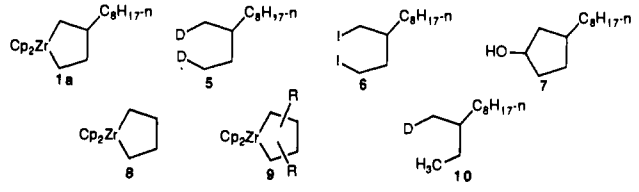
0002-7863/91/1513-6266$02.50/0

Scheme I



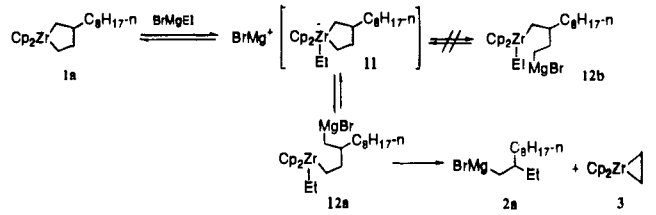
these transformations can not only be discretely observed as stoichiometric reactions but also be combined to provide a Zr-catalyzed process for converting alkenes and EtMgBr into 2-alkyl- and/or 1-aryl-substituted butylmagnesium bromides (Scheme I). Zirconium-catalyzed carbometalation reactions of both alkynes[4] and alkenes[5] are known, and a mechanism involving direct addition of the metal–carbon bond to alkynes has been presented for the alkyne reaction.[4d] The results presented herein, however, shed a novel mechanistic insight strongly indicating that, in sharp contrast with the alkyne addition reaction, the Zr-catalyzed carbomagnesation of alkenes likely proceeds via formation of zirconacyclopentanes.

Typically, Cp_2ZrCl_2 dissolved in THF was treated at −78 °C with 2 equiv of EtMgBr in THF. After 1 h, 1-decene (1 equiv) was added, and the mixture was stirred at 0 °C for several hours. Quenching of the mixture with 3 N HCl followed by distillative workup gave an 82% yield of ≥98% isomerically pure 3-methylundecane. Similarly, quenching with D_2SO_4 and I_2 produced 3-(deuteriomethyl)-1-deuterioundecane (**5**) and 1,4-diiodo-2-*n*-octylbutane (**6**), respectively. The extents of deuterium incorporation in **5** were >90% in the terminal CH_2D group and >98% in the 3-CH_2D group. That the organozirconium compound produced above was 1,1-bis(η^5-cyclopentadienyl)-3-*n*-octyl-1-zirconacyclopentane (**1a**) was further indicated by the ^1H NMR (C_6D_6) spectrum of the reaction mixture, which displayed the Cp signals at δ 6.04 and 6.06 ppm, and the ^{13}C NMR (C_6D_6) spectrum (14.12, 23.07, 23.82, 27.48, 29.87, 30.27, 30.52, 32.39, 35.60, 39.79, 45.07, 46.28, 106.55, and 111.49 ppm), as well as carbonylation–protonolysis at −78 °C of **1a** to give a 70:30 diastereomeric mixture of 3-*n*-octylcyclopentanol (**7**). The reaction of 1-alkenes with Et_2ZrCp_2 can, in principle, produce a mixture of **1**, **8**, and **9**. The reaction described above did not yield more than traces of any dimers of 1-decene, indicating that the reaction is not only regioselective but also "pair" selective.



Treatment of **1a** with 1 equiv of EtMgBr followed by quenching with D_2SO_4 in D_2O provided an 82% GLC yield of 3-(deuteriomethyl)undecane (**10**) with >90% D incorporation only at the 3-methyl carbon atom. The extent of D incorporation at the 1-methyl carbon atom is negligible (<2%). Examination by ^{13}C NMR spectroscopy of the reaction mixture before quenching indicates the formation of (2-ethyldecyl)magnesium bromide (**2a**)[6] in ca. 80% yield in a regioselective manner. Addition of PMe_3 (2 equiv) to the above reaction mixture produced, as expected, $Cp_2Zr(CH_2CH_2)(PMe_3)$[3d,e] (**4**) in >63% yield. Although we have not yet fully clarified the mechanistic details of the reaction, one likely mechanism is that shown in Scheme II. The remarkably high regioselectivity observed in this novel transformation must be largely steric in origin, and conversion of **11** to **12a** must be strongly favored relative to that to **12b**. This interpretation is strongly supported by nearly exclusive (>97%) formation of **4** in 73% yield from treatment with PMe_3 of $Cp_2ZrEt(C_{10}H_{23}$-*n*) generated by the reaction of $Cp_2ZrCl(C_{10}H_{23}$-*n*) with EtMgBr.

Scheme II



One significant consequence of the mechanistic consideration summarized in Scheme II is that the overall transformation should be catalytic in Zr. Specifically, addition of 1-decene should convert **3** into **1a** to complete a catalytic cycle. Indeed, the reaction of 1-decene with EtMgBr (2 equiv) in THF in the presence of only 0.1 equiv of Cp_2ZrCl_2 at 0 °C for 24 h gave **2a** in 80% yield. Examination of the reaction mixture by ^1H NMR indicated the buildup of **1a** (δ 6.44 ppm).[7] Here again, addition of PMe_3 (1.2 equiv relative to Cp_2ZrCl_2) resulted in a nearly quantitative yield of **4**. The use of 0.1 equiv of preformed **1a** as a catalyst in place of Cp_2ZrCl_2 yielded essentially the same results. Treatment of **2a** with I_2, allyl bromide, or MeI provided ≥98% isomerically pure 1-iodo-2-ethyldecane (74%), 5-ethyl-1-tridecene (71%), or 3-ethylundecane (80%), respectively, in the isolated yields shown in parentheses. Similarly, the use of 1-octene in place of 1-decene provided (2-ethyloctyl)magnesium bromide (**2b**). No significant difference between THF and ether was observed.

The reaction of styrene with EtMgBr (3 equiv) in the presence of Cp_2ZrCl_2 (0.1 equiv) for 24 h selectively provided a 95% yield of **2c**,[8] which was quenched with D_2SO_4 in D_2O to give **13** in 95% GLC yield (>99% D). A similar reaction of (*E*)-β-methylstyrene afforded in 98% yield a 60:40 diastereomeric mixture of **14**[9] which was analogously converted to **15** in 90% (98% GLC) yield (>96% D). We have so far failed to observe a similar reaction with (*E*)- or (*Z*)-stilbene, which remained unreacted except for the previously reported *Z*-to-*E* isomerization.[2b] The stoichiometric reaction of styrene or (*E*)-β-methylstyrene with 2 equiv of EtMgBr and 1 equiv of Cp_2ZrCl_2 gave >98% isomerically pure **1c** or **16**, respectively, which was converted to **17** (70%) or **18** (96%), respectively. Carbonylation of **16** followed by protonolysis and PCC oxidation gave **19**, which was shown to be the trans isomer by ^1H 2D NOESY NMR spectroscopy. The reaction of styrene or β-methylstyrene with $Cp_2Zr(Bu$-*n*$)_2$ gave regioselectively **20** (85%) or **21** (96%),[2a] respectively, which was then treated with EtMgBr (2.5 equiv) at 0 °C for 24 h. The product thus formed was deuterolyzed with D_2SO_4 in D_2O to give **22** or **23**, respectively. While **22** was >95% regiochemically pure, **23** was a 3:1 mixture of the 1-deuterio and 4-deuterio isomers. The reaction of 1-decene with *n*-PrMgBr in THF catalyzed by 0.1 equiv of Cp_2ZrCl_2 for

(4) (a) For a review, see: Negishi, E. *Pure Appl. Chem.* **1981**, *53*, 2333. (b) Van Horn, D. E.; Negishi, E. *J. Am. Chem. Soc.* **1978**, *100*, 2252. (c) Rand, C. L.; Van Horn, D. E.; Moore, M.; Negishi, E. *J. Org. Chem.* **1981**, *46*, 4093. (d) Yoshida, T.; Negishi, E. *J. Am. Chem. Soc.* **1981**, *103*, 4985. (e) Negishi, E.; Van Horn, D. E.; Yoshida, T.; Rand, C. L. *Organometallics* **1983**, *2*, 563.

(5) (a) For a review, see: Dzhemilev, U. M.; Vostrikova, O. S.; Tolstikov, G. A. *J. Organomet. Chem.* **1986**, *304*, 17. (b) Dzhemilev, U. M.; Vostrikova, O. S.; Sultanov, R. M. *Izv. Akad. Nauk SSSR, Ser. Khim.* **1983**, 219. (c) For a recent paper reporting the stoichiometric formation of zirconacyclopentanes from alkenes, Et_3Al, and Cp_2ZrCl_2, see: Dzhemilev, U. M.; Ibragimov, A. G.; Zolotarev, A. P.; Muslukhov, R. R.; Tolstikov, G. A. *Izv. Akad. Nauk SSSR, Ser. Khim.* **1989**, 194.

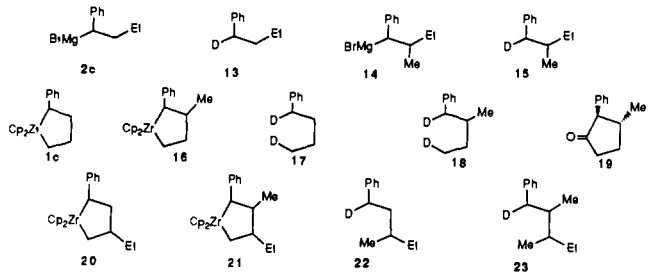
(6) **2a**: ^{13}C NMR (C_6D_6) δ 12.65, 14.28, 14.49, 23.00, 28.51, 29.85, 30.36, 30.93, 32.30, 34.36, 40.62, 41.85.

(7) The ^1H NMR signals for the two nonequivalent Cp rings were seen as a somewhat broadened singlet.

(8) **2c**: ^{13}C NMR (C_6D_6) δ 14.95, 25.24, 35.52, 38.20, 127.76, 128.00, 128.24, 128.32.

(9) **2d**: ^{13}C NMR (C_6D_6) δ 11.78 and 12.89, 21.10 and 23.39, 30.66 and 34.07, 37.25, and 37.90, 47.38 and 49.09, 123.87, 128.36, 128.48, 157.90.

36 h at 25 °C gave, after hydrolysis, only a 22% yield of 2,3-dimethylundecane. The reaction of either 1-decene or styrene with MeMgBr (2 equiv) in the presence of 0.2 equiv of Cp_2ZrCl_2 in THF at 25 °C did not produce the desired methylation product. It did, however, produce a good yield of Cp_2ZrMe_2 based on Zr.



Acknowledgment. We thank Kawakami Memorial Foundation, Japan, and the National Science Foundation (CHE-8921899) for support of this research. We also thank Professor R. M. Waymouth of Stanford University for informing us of his related study prior to publication.

Registry No. 1a, 133817-48-8; **1c**, 133817-49-9; **2a**, 133817-34-2; **2b**, 133817-36-4; **2c**, 133817-37-5; **4**, 119366-91-5; **5**, 133817-29-5; **6**, 133817-30-8; *cis*-**7**, 133817-32-0; *trans*-**7**, 133817-31-9; **10**, 133817-33-1; **13**, 4397-69-7; (*R**,*R**)-**14**, 133817-38-6; (*R**,*S**)-**14**, 133817-39-7; **15**, 133817-40-0; **16**, 133817-50-2; **17**, 133817-41-1; **18**, 133817-42-2; **19**, 133817-43-3; **20**, 133869-10-0; **21**, 133817-51-3; **22**, 133817-44-4; **23**-*l*-d_1, 133817-45-5; **23**-*4*-d_1, 133817-46-6; Cp_2ZrCl_2, 1291-32-3; $Cp_2Zr(Bu\text{-}n)_2$, 80005-41-0; Cp_2ZrMe_2, 12636-72-5; $Cp_2ZrEt(C_{10}H_{23}\text{-}n)$, 133817-52-4; $Cp_2ZrCl(C_{10}H_{23}\text{-}n)$, 133817-53-5; EtMgBr, 925-90-6; *n*-PrMgBr, 927-77-5; MeMgBr, 75-16-1; 1-decene, 872-05-9; 3-methylundecane, 1002-43-3; 5-ethyl-1-tridecene, 133817-35-3; 3-ethylundecane, 17312-58-2; 1-octene, 111-66-0; styrene, 100-42-5; (*E*)-β-methylstyrene, 873-66-5; (*E*)-stilbene, 103-30-0; (*Z*)-stilbene, 645-49-8; 2,3-dimethylundecane, 17312-77-5; 3-iodomethylundecane, 133817-47-7.

Supplementary Material Available: Representative synthetic procedures and spectral data (2 pages). Ordering information is given on any current masthead page.

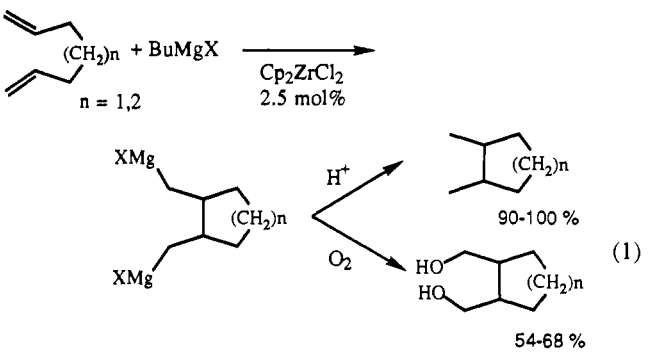
Zirconium-Catalyzed Diene and Alkyl-Alkene Coupling Reactions with Magnesium Reagents

Kyle S. Knight and Robert M. Waymouth*

Department of Chemistry, Stanford University
Stanford, California 94305
Received December 10, 1990

Zirconium complexes have found extensive application as stoichiometric reagents in organic synthesis.[1] The development of chiral zirconocenes[2,3] and their successful application as stereospecific olefin polymerization catalysts[4,5] have stimulated renewed interest in the development of early-transition-metal chemistry for enantioselective synthesis.[3] However, the multistep synthesis and resolution of these chiral metallocenes presents a severe limitation in the application of these complexes for stoichiometric organic transformations; practical applications will likely require catalytic methods. As part of our efforts to develop the catalytic chemistry of group 4 metallocenes,[5] we were attracted to a report[6] of catalytic carbometalation of olefins mediated by zirconocenes and dialkylmagnesium reagents. Herein we report our studies of these reactions and the development of a zirconium *catalyst* for the reductive coupling of dienes to yield magnesium reagents.

Zirconocene derivatives generated from zirconocene dichloride and butyllithium[7] have previously been shown to be highly efficient stoichiometric reagents for the regio- and stereoselective reductive cyclization of nonconjugated dienes,[8] diynes, and enynes.[9] We have found that, in the presence of Bu_2Mg[10] or BuMgCl, the diene cyclization reactions are *catalytic in zirconium*. For example, treatment of 1,7-octadiene with Bu_2Mg (1.5 equiv) or BuMgCl (3.0 equiv) in the presence of 2.5% zirconocene dichloride in ether at room temperature for 24 h yields, upon hydrolysis, 1,2-dimethylcyclohexane in excellent yield (eq 1, Table I). Deuterolysis of the reaction mixture with 10% D_2SO_4/D_2O affords 1,2-bis(deuteriomethyl)cyclohexane (93% d_2).[11] Oxidative workup (O_2, Et_2O, −78 °C)[12] gives the diol product, 1,2-bis(hydroxymethyl)cyclohexane. The stereochemistry of the cyclization of 1,7-octadiene (82:18 cis:trans) is similar to that seen in stoichiometric reactions.[8] In contrast, the catalytic cyclization of 1,6-heptadiene with Bu_2Mg occurs with lower stereoselectivity (36:64 cis:trans) than is observed in stoichiometric reactions with BuLi (3:97 cis:trans).[8] At this time, the origin of the different stereoselectivities is not known; it is possible that the metallacycle intermediates can isomerize[9b] under the reaction conditions (Scheme I).[13] Further studies are underway to address this possibility.



The use of Et_2Mg in place of Bu_2Mg gave a complex mixture of products in the reaction with octadiene. However, treatment of terminal alkenes with Et_2Mg or EtMgBr in the presence of

(1) (a) Harrington, P. J. *Transition Metals in Total Synthesis*; Wiley: New York, 1990; p 414. (b) Cardin, D. J.; Lappert, M. F.; Raston, C. L. *Chemistry of Organozirconium and Hafnium Compounds*; Ellis Horwood Limited: Chichester, 1986. (c) Negishi, E. *Acc. Chem. Res.* **1987**, *20*, 65-72.

(2) (a) Wild, F. R. W. P.; Zsolnai, L.; Huttner, D. S.; Britzinger, H. H. *J. Organomet. Chem.* **1982**, *232*, 233. (b) Wild, F. R. W. P.; Zsolnai, L.; Huttner, D. S.; Britzinger, H. H. *J. Organomet. Chem.* **1985**, *288*, 63.

(3) (a) Collins, S.; Kuntz, B. A.; Hong, Y. *J. Org. Chem.* **1989**, *54*, 4154-4158. (b) Halterman, R. L.; Vollhardt, K. P. C. *Organometallics* **1988**, *7*, 883-892. (c) Halterman, R. L.; Vollhardt, K. P. C. *J. Am. Chem. Soc.* **1987**, *109*, 8105-8107. (d) Paquette, L. A.; Moriarty, K. J.; McKinney, J. A.; Rogers, R. D. *Organometallics* **1989**, *8*, 1707-1713. (e) Erker, G.; van der Zeijden, A. A. H. *Angew. Chem., Int. Ed. Engl.* **1990**, *29*, 512. (f) Couturier, S.; Tainturier, G.; Gautheron, B. *J. Organomet. Chem.* **1980**, *195*, 291.

(4) (a) Ewen, J. A.; Jones, R. L.; Razavi, A.; Ferrara, J. D. *J. Am. Chem. Soc.* **1988**, *110*, 6255 and references therein. (b) Kaminsky, W.; Kulper, K.; Brintzinger, H. H.; Wild, F. R. W. P. *Angew. Chem., Int. Ed. Engl.* **1985**, *24*, 507-508. (c) Kaminsky, W.; Moller-Lindenhof, N. *Bull. Soc. Chim. Belg.* **1990**, *99*, 103 and references therein. (d) Pino, P.; Cioni, P.; Wei, J. *J. Am. Chem. Soc.* **1987**, *109*, 6189. (e) Spalek, W.; Antberg, M.; Dolle, V.; Klein, R.; Rohrmann, J.; Winter, A. *New J. Chem.* **1990**, *14*, 499.

(5) (a) Waymouth, R.; Pino, P. *J. Am. Chem. Soc.* **1990**, *112*, 4911-4914. (b) Resconi, L.; Waymouth, R. M. *J. Am. Chem. Soc.* **1990**, *112*, 4953-4954.

(6) (a) Dzhemilev, V. M.; Vostrikova, O. S. *J. Organomet. Chem.* **1985**, *285*, 43-51. (b) Dzhemilev, V. M.; Vostrikova, O. S.; Tolstikov, A. *J. Organomet. Chem.* **1986**, *304*, 17.

(7) Negishi, E.-i.; Cederbaum, F. E.; Takahashi, T. *Tetrahedron Lett.* **1986**, *27*, 2829-2832.

(8) (a) Nugent, W. A.; Taber, D. F. *J. Am. Chem. Soc.* **1989**, *111*, 6435-6437. (b) Rousset, C. J.; Swanson, D. R.; Lamaty, F.; Negishi, E.-i. *Tetrahedron Lett.* **1989**, *30*, 5105-5108.

(9) (a) Negishi, E.-i.; Swanson, D. R.; Cedarbaum, F. E.; Takahashi, T. *Tetrahedron Lett.* **1987**, *28*, 917-920. (b) Swanson, D. R.; Rousset, C. J.; Negishi, E.-i. *J. Org. Chem.* **1989**, *54*, 3521-3523. (c) RajanBabu, T. V.; Nugent, W. A.; Taber, D. T.; Fagan, P. J. *J. Am. Chem. Soc.* **1988**, *110*, 7128-7135. (d) Negishi, E.-i.; Holmes, S. J.; Tour, J. M.; Miller, J. A.; Cederbaum, F. E.; Swanson, D. R.; Takahashi, T. *J. Am. Chem. Soc.* **1989**, *111*, 3336. (e) Lund, E. C.; Livinghouse, T. *J. Org. Chem.* **1989**, *54*, 4487-4488.

(10) Conveniently prepared from the Grignard reagent. Saheki, Y.; Sasada, K.; Satoh, N.; Kawaichi, N.; Negoro, K. *Chem. Lett.* **1987**, 2299-2300.

(11) Determined by ^{13}C NMR and high-resolution mass spectrometry. Budzikiewicz, H.; Djerassi, C.; Williams, D. H. *Structural Elucidation of Natural Products By Mass Spectrometry*; Holden Day: **1964**, p 34-36.

(12) Walling, C.; Ciaoffari, A. *J. Am. Chem. Soc.* **1970**, *92*, 6609.

(13) The temperature of the catalytic reactions is 25 °C, whereas stoichiometric reactions are carried out between −78 and 25 °C.

0002-7863/91/1513-6268$02.50/0