Zirconocene-Mediated Cyclization of 2-Bromo α,ω-Dienes

Dan B. Millward and Robert M. Waymouth*

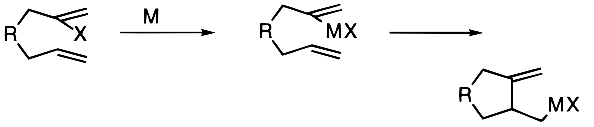
Department of Chemistry, Stanford University, Stanford, California 94305

Received October 14, 1996⊗

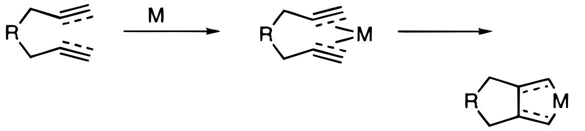
When it is first treated with *n*-butyllithium at −78 °C, zirconocene dichloride is an effective reagent for the cyclization of some 2-bromo α,ω-dienes at 25 °C. The products are carbo- and heterocyclic five-membered rings with adjacent methylene and methyl substituents. Reductive cyclization to form zirconacyclopentanes, followed by β-bromo elimination, is indicated as the order of steps in the reaction mechanism. Use of catalytic zirconocene dichloride with excess butylmagnesium chloride in diethyl ether at 25 °C is effective only for cyclization of 2-bromo-1,6-heptadiene.

Introduction

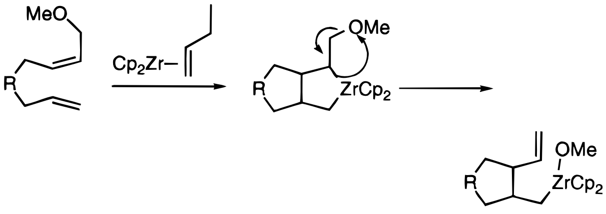
Transition-metal-mediated cyclization strategies which form new carbon−carbon bonds are among the most important methods in the synthesis of carbo- and heterocyclic ring structures.[1] Two common mechanistic motifs in metal-mediated cyclizations are illustrated in eqs 1 and 2. One strategy involves oxidative addition followed by olefin insertion and is most commonly carried out with late transition metals such as palladium[2−7] (the Heck reaction) and nickel.[8−11] Another strategy involves intramolecular reductive coupling and is seen with both later transition metals such as cobalt[12] (the Pauson−Khand reaction) and early transition metals such as reduced zirconocenes.[13−22] Examples of both stoichiometric[8−11,13−21] and catalytic[4−7,22,23] use of metal complexes are known. We have observed that zirconocene-mediated cyclization of terminal allylmethoxy diene substrates affords carbocyclic products with adjacent vinyl and methyl groups under both stoichiometric and catalytic conditions (eq 3).[22b] β-Methoxy elimination from a zirconacyclopentane intermediate accounts for the vinyl functionality. Takahashi has also observed β-alkoxy elimination in intermolecular olefin couplings with zirconium.[24,25] Recently, Takahashi has reported the formal oxidative addition of 2-halopropenes to reduced zirconocenes to yield 2-propenylzirconocene halides via a proposed β-halo elimination from a 2-halo-2-methyl-1-zirconacyclopropane intermediate.[26] Herein we report the cyclization of 2-bromo-α,ω-dienes to *exo*-methylenemethylcycloalkanes and studies to address the mechanism of cyclization.



(1)



(2)



(3)

Results

The zirconocene (1-butene) adduct generated *in situ* with the Negishi method[27] reacts stoichiometrically with

---

⊗ Abstract published in *Advance ACS Abstracts,* February 1, 1997.

(1) Trost, B. M. *Science* **1991**, *254*, 1471.

(2) Grigg, R.; Stevenson, P.; Worakun, T. *J. Chem. Soc., Chem. Commun.* **1984**, 1073−1075.

(3) Ziegler, F. E.; Chakraborty, U. R.; Weisenfeld, R. B. *Tetrahedron* **1981**, *37*, 4035.

(4) Overman, L.; Abelman, M.; Kucera, D.; Tran, V.; Ricca, D. *Pure Appl. Chem.* **1992**, *64*, 1813.

(5) Meyer, F.; Brandenburg, J.; Parsons, P.; de Meijere, A. *J. Chem. Soc., Chem. Commun.* **1992**, 390.

(6) Meyer, F.; Parsons, P.; de Meijere, A. *J. Org. Chem.* **1991**, *56*, 6487.

(7) Chida, N.; Ohtsuka, M.; Ogawa, S. *J. Org. Chem.* **1993**, *58*, 4441.

(8) Llebaria, A.; Camps, F.; Moreto, J. M. *Tetrahedron Lett.* **1992**, *33*, 3683.

(9) Llebaria, A.; Delgado, A.; Camps, F.; Moreto, J. M. *Organometallics* **1993**, *12*, 2825.

(10) Delgado, A.; Llebaria, A.; Camps, F.; Moreto, J. M. *Tetrahedron Lett.* **1994**, *35*, 4011.

(11) Sole, D.; Cancho, Y.; Llebaria, A.; Moreto, J.; Delgado, A. *J. Am. Chem. Soc.* **1994**, *116*, 12133.

(12) Billington, D. C.; Pauson, P. L. *Organometallics* **1982**, *1*, 1560.

(13) Negishi, E.; Cederbaum, F. R.; Takahashi, T. *Tetrahedron Lett.* **1986**, *27*, 1989.

(14) Negishi, E.; Holmes, S. J.; Tour, J. M.; Miller, J. A.; Cederbaum, F. R.; Takahashi, T. *J. Am. Chem. Soc.* **1989**, *111*, 3336.

(15) Nugent, W. A.; Thorn, D. L.; Harlow, R. L. *J. Am. Chem. Soc.* **1987**, *109*, 2788.

(16) Rajanbabu, T. V.; Nugent, W. A.; Taber, D. F.; Fagan, P. J. *J. Am. Chem. Soc.* **1988**, *110*, 7128.

(17) Negishi, E.; Holmes, S. J.; Tour, J. M.; Miller, J. A. *J. Am. Chem. Soc.* **1985**, *107*, 2568.

(18) Negishi, E.; Swanson, D. R.; Cederbaum, R. E.; Takahashi, T. *Tetrahedron Lett.* **1987**, *28*, 917.

(19) Swanson, D. R.; Rousset, C. J.; Negishi, E. *J. Org. Chem.* **1989**, *54*, 3521.

(20) Nugent, W. A.; Taber, D. F. *J. Am. Chem. Soc.* **1989**, *111*, 6435.

(21) Rousset, C. J.; Swanson, D. R.; Lamaty, F.; Negishi, E. *Tetrahedron Lett.* **1989**, *30*, 5105.

(22) (a) Knight, K.; Wang, D.; Waymouth, R. M.; Ziller, J. *J. Am. Chem. Soc.* **1994**, *116*, 1845. (b) Knight, K.; Waymouth, R. M. *Organometallics* **1994**, *13*, 2575.

(23) Hicks, F. A.; Kablaoui, N. M.; Buchwald, S. L. *J. Am. Chem. Soc.* **1996**, *118*, 9450−9451.

(24) Suzuki, N.; Kondakov, D. Y.; Takahashi, T. *J. Am. Chem. Soc.* **1993**, *115*, 8485−8486.

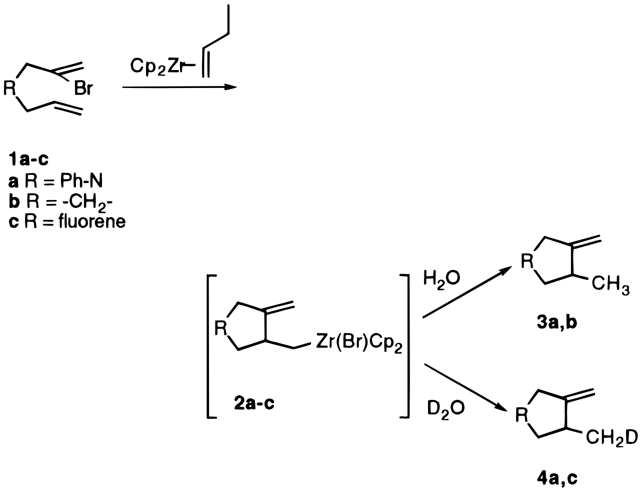
(25) Takahashi, T.; Kondakov, D. Y.; Xi, Z.; Suzuki, N. *J. Am. Chem. Soc.* **1995**, *117*, 5871−5872.

(26) Takahashi, T.; Kotora, M.; Fischer, R.; Nishihara, Y.; Nakajima, K. *J. Am. Chem. Soc.* **1995**, *117*, 11039.

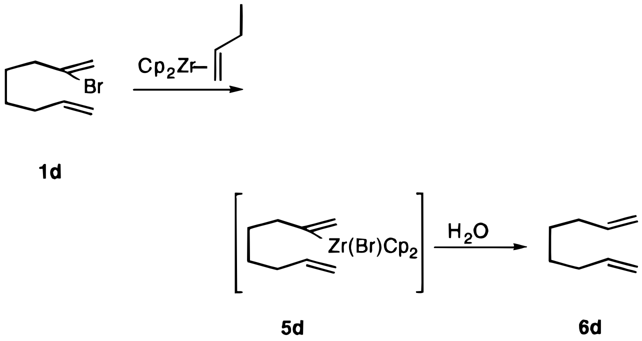
(27) Negishi, E.; Cederbaum, F. E.; Takahashi, T. *Tetrahedron Lett.* **1986**, *27*, 2829.

S0276-7333(96)00870-9 CCC: $14.00

Scheme 1. Cyclization of 2-Bromo α,ω-Dienes



Scheme 2. Oxidative Addition of 2-Bromo-1,7-octadiene



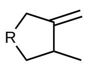
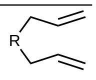
N-(3-propenyl)-*N*-(2-bromo-3-propenyl)aniline (**1a**) in ether to yield the 4-(zirconocenylmethyl)-3-methylene-1-phenylpyrrolidine species **2a** in 1 h, as determined by hydrolysis and deuterolysis (Scheme 1). Similarly, 2-bromo-1,6-heptadiene **1b** and 9-(3-propenyl)-9-(2-bromo-3-propenyl) fluorene **1c** react under the same conditions to give the expected products **3b** and **4c** after hydrolysis/deuterolysis, but 2-bromo-1,7-octadiene **1d** yields almost entirely 1,7-octadiene **6d** upon hydrolysis (Scheme 2). The results are summarized in Table 1.[28]

Attempts to generate and characterize the putative cyclized organometallic intermediates **2a** and **2c** met with mixed success. While ^{1}H NMR spectra of aliquots taken from the reaction flask after 1 h indicated the formation of the desired products, efforts to grow X-ray diffraction quality crystals were unsuccessful. Attempts to isolate **2a** led to an uncharacterizable, insoluble material, which upon hydrolysis yielded primarily **3a**.

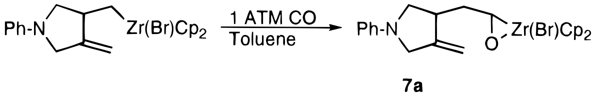
Attempts to characterize **2b** by reacting with iodine, *N*-bromosuccinimide, or O_2 were unsuccessful. However, carbonylation of **2a** with 1 atm of CO yielded the acylzirconocene bromide species **7a** (eq 4). ^{1}H and ^{13}C NMR analyses of isolated **7a** support the suggested structure.

Deuterolysis studies were performed to probe the structure of the organometallic intermediates. The position of the incorporated deuterium atom was dependent on the nature of the substrate. The ^{2}H and ^{13}C NMR spectra of **4a** and **4c** (derived from the aniline and fluorene substrates, respectively**)** indicate uptake of a single deuterium exclusively on the methyl group. However, analysis of deuterolyzed **2b** (derived from 2-bromo-1,6-heptadiene) by ^{2}H NMR indicated that deuterium is incorporated at allylic positions. Analysis of deuteriolyzed **2b** by GC/MS suggests that much of the deuterium is on the carbocyclic ring rather than on a pendant methyl group.

Table 1. Stoichiometric Cyclization of 2-Bromo α,ω-Dienes

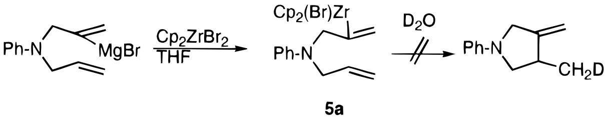
diene	R	conversn,[a] %	yield,[a] %	
				
1a	Ph−N	96	96	
1b	$-CH_2-$	98	73	
1c	9,9-fluorene	92	75	12
1d	$-CH_2CH_2-$	91	4	66

[a] Percent conversion and yield determined by GC analysis.



(4)

To further probe the nature of the zirconocene intermediates in these reactions, the vinylzirconocene complexes **5a** and **5b** were prepared independently. Treatment of zirconocene dibromide with 1 equiv of the Grignard reagent formed from **1a** in THF generated **5a** *in situ*, as indicated by ^{1}H NMR analysis. However, GC analysis of hydrolyzed aliquots showed that *no olefin insertion occurred* (leading to either **3a** or **3b**) over the course of 12 h (eq 5).



(5)

Efforts to cyclize **1a**−**d** catalytically in the presence of 10 mol % Cp_2ZrCl_2 and excess butylmagnesium chloride in diethyl ether at room temperature met with limited success, as shown in Table 2. Attempts to catalyze the cyclization of **1a** with zirconium were unsuccessful. Both **1b** and **1c** cyclize catalytically with zirconium, although the reaction is slow, and conversion and product yields are moderate to poor. Substrate **1d** affords more of the cyclized product 2-methyl-1-methylenecyclohexane (**3d**) under these conditions relative to the stoichiometric reaction, although the major product upon quenching with H_2O is still 1,7-octadiene (**6d**). GC/MS analysis of the deuterium-quenched catalytic reaction of **1b** indicates uptake of two deuterium atoms in more than half of the product. The ^{2}H spectrum of these products shows the two signals seen in the stoichiometric reaction, as well as two peaks further downfield, at positions not seen in the ^{1}H spectrum of independently synthesized 2-methyl-1-methylenecyclopentane.

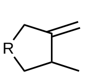
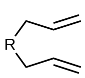
Discussion

Zirconocene (oxidation state II) is capable of mediating a stoichiometric Heck-type cyclization of 2-bromo-

---

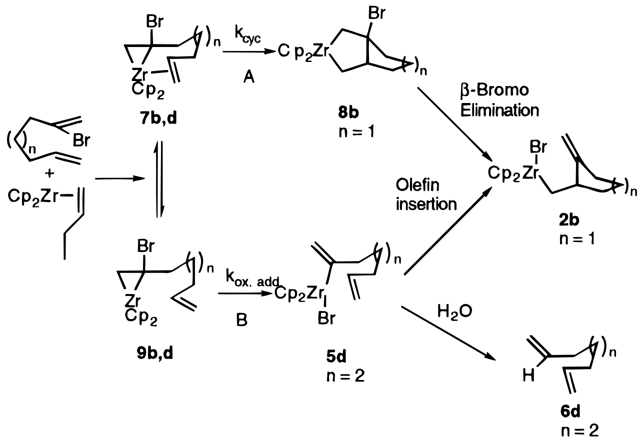
[28] Initially, we intended to investigate the 2-chloro α,ω-diene series of these substrates as well. Unfortunately, varied attempts to synthesize and isolate 2-chloro-1,6-heptadiene were unsuccesful; therefore, the more tractable 2-bromo α,ω-dienes became the focus of this investigation.

Table 2. Catalytic Cyclization of 2-Bromo α,ω-Dienes

				yield,[a] %	
diene	R	time, h	conversn,[a] %		
1a	Ph−N	24	10	10	
1b	−CH$_2$−	24	28	15	
		96	43	35	
1c	9,9-fluorene	24	55	25	
		60	90	38	
1d	−CH$_2$CH$_2$−	4	69	9	28

[a] Percent conversion and yield determined by GC analysis.

Scheme 3. Possible Mechanism for Cyclization of 2-Bromo α,ω-Dienes

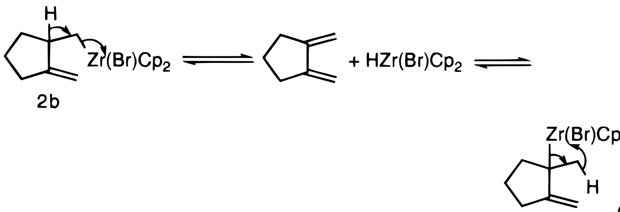


1,6-heptadiene (**1b**) and analogues **1a** and **1c** to α-methyl methylenecycloalkanes. A possible reaction mechanism involves the reductive cyclization of the ω-olefin vinyl bromide to the metallacycles **8a**−**c**, followed by β-bromo elimination to generate α-zirconocenylmethyl methylenecycloalkanes **2a**−**c**, which upon hydrolysis yield **3a**−**c** (Scheme 3A). Related β-alkoxy eliminations have been observed by us and others.[23−25] However, as Takahashi has observed the oxidative addition of vinyl bromides to zirconocene (oxidation state II), another possible mechanism would involve the oxidative addition of the vinyl bromide followed by an insertion of the pendant olefin into the Zr−vinyl bond (Heck type, Scheme 3B).

We carried out several experiments to probe the viability of either pathway. The fact that attempts to cyclize 2-bromo-1,7-octadiene (**1d**) yielded only the reduced 1,7-octadiene upon hydrolysis suggest that oxidative addition is clearly a reasonable pathway for these substrates. However, as very little cyclized product is seen, olefin insertion does not appear to be a viable mechanistic step, at least when there are four other atoms between the carbon atoms to be coupled. To further determine whether the oxidative-addition compound **5** would cyclize to **2**, we independently prepared **5a** and **5c** from the Grignard reagents of aniline substrate **1a** and the 2-bromo-1,6-heptadiene species **1c**. These materials did not cyclize to **2a** or **2c,** respectively, which suggests that intramolecular cyclization of **5** via olefin insertion is not a facile process and implies that the cyclization of **1a**−**c** proceeds by the mechanism depicted in Scheme 3A.

One possible explanation for the selective cyclization of substrates resulting in five-membered-ring products depends on competitive reaction rates for reductive cyclization and oxidative addition as depicted in Scheme 3. If an equilibrium exists between organometallic olefin adduct species **7** and **9**, product determination will depend on the ensuing rates of cyclization and addition. For the heptadiene-type substrates **1a**−**c**, cyclization would be expected to be the faster step in this mechanism, whereas for the longer chain substrate 2-bromo-1,7-octadiene (**1d**), cyclization might not be competitive with oxidative addition, as indicated by Scheme 3B.

Attempts to isolate and characterize compounds **2a**−**c** were frustrated by apparent decomposition, likely occurring through a reversible β-hydride elimination process. Furthermore, deuterolysis of **2b,** generated *in situ*, placed the deuterium at two distinct chemical shifts, neither corresponding to the chemical shift of the protons on the pendant methyl group of authentic **3b** generated independently via Wittig olefination of 2-methylcyclopentanone. This observation of deuterium incorporation at allylic positions may be accounted for by β-hydride elimination from ((homoallylic)alkyl)zirconocene bromide **2b** followed by readdition of the zirconocene hydride to place the zirconium on the allylic ring carbon (eq 6). The possibility of further rearrangement and “walking” the metal around the ring must also be considered as possibilities which could generate more than one product. The fact that deuterium incorporation is only observed on the pendant methyl upon deuterolysis of **2a** and **2c** may be explained either through invoking a much slower β-hydride process or through unfavorable addition of zirconocene at the allylic carbon. Either argument may be supported by the increased steric demands of the aniline and fluorene substrates and by the potential for heteroatom coordination to zirconium for the aniline substrate.

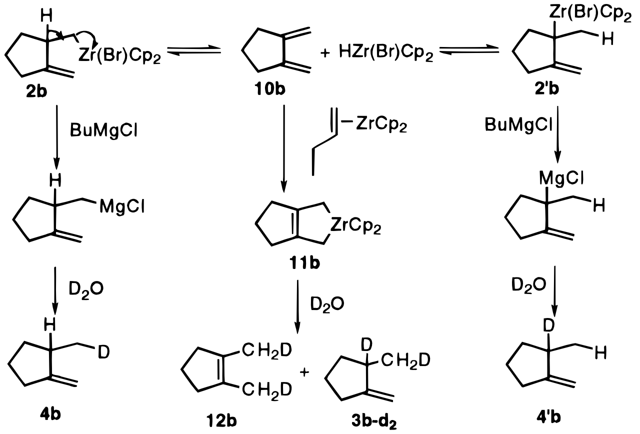


(6)

The poor reactivity of substrates **1a**−**c** with catalytic zirconocene was unexpected but may be due to the competitive β-hydride-elimination process. Substrate **1a** reacts stoichiometrically with 10 mol % zirconocene, which suggests formation of a metal complex which is unreactive to butylmagnesium chloride. As only this heteroatom-containing substrate reacts this way, coordination of the nitrogen lone pair to the metal center seems likely to be responsible for this lack of reactivity. Donation of the nitrogen lone pair in complex **2a** would fill the 18-electron shell of the metal and decrease its electrophilicity. Substrates **1b** and **1c** react slowly with catalytic zirconocene, but only **1b** generates primarily the cyclic product **3b**, as determined by co-GC with an authentic sample. The observation of extensive incorporation of two deuterium atoms in D$_2$O-quenched reactions of **1b** and catalytic zirconocene can be accounted for as shown in Scheme 4.

β-Hydride elimination from **2b** would generate the 1,3-diene **10b**, and dienes of this type are known to react with reduced zirconocene to form zirconacyclopentenes

Scheme 4. Possible Scrambling Processes



such as compound **11b**. Deuterolysis of complexes such as **11b** would afford dideuterated organic products such as **3b-*d*$_2$** and **12b**. The unusual chemical shifts seen in the ^{2}H NMR spectrum lend credence to the formation of products other than 2-(deuteriomethyl)-1-methylenecyclopentane (**4b**) alone. A complex competition between the rates of β-hydride elimination, butyl Grignard reaction with zirconocene alkene bromides **2b** and **2′b**, zirconocene bromide hydride addition into alkenes, and reduced zirconocene reaction with 1,3-diene is probably occurring to afford a mixture of mono- and dideuterated products.

In summary, 2-bromo α,ω-dienes react with a stoichiometric reduced zirconocene to afford cyclized *exo*-methylene products only if a five-membered ring is formed. The cyclization process must occur before β-bromo elimination, as olefin insertion into zirconocene alkene bromide complexes does not occur. Competition between the rates of cyclization and β-bromo elimination accounts for the selective cyclization of heptadienes but not octadienes. The catalytic cyclization of 2-bromoheptadiene with zirconocene dichloride and excess butylmagnesium chloride is slow, gives low yields of product, and generates many side products.

Experimental Section

General Considerations. All manipulations involving air-sensitive compounds were carried out under nitrogen in a glovebox or under argon using standard Schlenk-line techniques. Zirconocene dichloride was purchased from Strem. Solutions of *n*-butyllithium in hexanes and *n*-butylmagnesium chloride were purchased from Aldrich and used as received. Technical grade (85%) 2,3-dibromopropene was purchased from Aldrich and fractionally distilled prior to use. All solvents except toluene were distilled or vacuum-transferred from Na/benzophenone prior to use. Toluene was purified by passing through columns of Q-5 and alumina under argon. GC analyses were obtained on a Hewlett-Packard 5890 chromatograph equipped with an SE-30 column. NMR experiments were performed on Varian Gemini 200 and XL-400 spectrometers. GC/MS data were taken on a Hewlett-Packard 5890 chromatograph equipped with an SE-54 column attached to a Hewlett-Packard 5970 mass spectrometer. Elemental analyses were performed by E+R Microanalytical Laboratory, Inc., and Desert Analytics.

***N*-(3-Propenyl)-*N*-(2-bromo-3-propenyl)aniline (1a).** In a 250 mL round-bottomed Schlenk flask, *N*-allylaniline (1.36 mL, 10 mmol) was dissolved in 50 mL of THF under argon. The flask was cooled to −78 °C, and 2.5 M *n*-butyllithium (4 mL, 10 mmol) was added. The solution was warmed to room temperature and then recooled to −78 °C, whereupon 2,3-dibromopropene (1.14 mL, 10 mmol) was added. The reaction mixture was warmed to room temperature and stirred for 9 h. It was then poured into 250 mL of 4:1 diethyl ether/saturated aqueous NH_4Cl and the organic layer separated. The aqueous phase was extracted with 100 mL of diethyl ether, which was then combined with the organic layer and washed with 50 mL of brine. The organics were dried over $MgSO_4$, and solvent was removed with a rotary evaporator to yield a dark brown crude oil. Flash chromatography in straight hexanes sufficed to purify the product, 1.335 g (54% yield) of a clear, yellow oil. The oil was dried over CaH_2, then distilled at 95 °C at 80 mTorr. ^{1}H NMR ($CDCl_3$): δ 2.72 (d, $J = 7$ Hz, 2H), 3.20 (s, 2H), 4.74−4.89 (m, 3H), 5.09 (d, $J = 1.8$ Hz, 1H), 5.13−5.30 (m, 1H), 7.25−7.46 (m, 6H), 7.71 (m, 2H). ^{13}C NMR: δ 53.1, 58.8, 112.5, 116.2, 116.8, 117.5, 129.5, 129.8, 133.5, 147.9. Anal. Calcd: C, 57.15; H, 5.60; N, 5.56; Br, 31.69. Found: C, 57.26; H, 5.61; N, 5.51; Br, 32.08.

2-Bromo-1,6-heptadiene (1b).[29] In a 100 mL round-bottomed Schlenk flask activated zinc powder (2.54 g, 38.8 mmol) and lithium iodide (0.505 g, 3.77 mmol) were slurried in 10 mL of DMA. Neat 1,2-dibromoethane (302 μL, 3.5 mmol, 0.27 equiv) was added to the slurry, which caused an exotherm. After the mixture was cooled to room temperature, 4-bromobutene (1.14 mL, 11.2 mmol) was added, and the solution was stirred for 12 h. A separate 100 mL round-bottomed Schlenk flask was charged with copper(I) cyanide (1.13 g, 12.6 mmol) and lithium bromide (2.13 g, 24.5 mmol, 2.2 equiv) which were then dissolved in 30 mL of THF. The zincate slurry was allowed to settle and then cannula-filtered into the copper solution, which was initially held at 0 °C and then warmed to room temperature. Neat 2,3-dibromopropene (1.15 mL, 10.2 mmol) was added, and the reaction mixture was stirred for 16 h. This mixture was worked up by pouring into 300 mL 5:1 diethyl ether/saturated aqueous NH_4Cl solution. The organic layer was separated and washed with saturated aqueous $NaHCO_3$ and then with brine. Removal of solvent with a rotary evaporator afforded a pale yellow oil, which was stirred over CaH_2 for 16 h and then vacuum-transferred to yield 1.7 g (88% yield) of product. ^{1}H NMR ($CDCl_3$): δ 1.66 (q, $J = 7.4$ Hz, 2H), 2.08 (m, 2H), 2.43 (t, $J = 7.5$ Hz, 2H), 5.01 (m, 2H), 5.40 (d, $J = 1.6$ Hz, 1H), 5.56 (d, $J = 1.2$ Hz, 1H), 5.79 (m, 1H). ^{13}C NMR: δ 27.0, 32.3, 40.6, 115.1, 116.6, 134.4, 137.9. Anal. Calcd: C, 48.02; H, 6.33; Br, 45.64. Found: C, 47.80; H, 6.65; Br, 45.23.

9-(3-Propenyl)-9-(2-bromo-3-propenyl)fluorene (1c).[30] An oven-dried 250 mL round-bottomed Schlenk flask was charged with fluorene (4.0 g, 24.1 mmol) under argon, which was then dissolved in 150 mL of THF. The solution was cooled to −78 °C, and 2.5 M *n*-butyllithium (9.7 mL, 24.1 mmol) was added. The solution was stirred and warmed to room temperature. Allyl bromide (2.1 mL, 24.1 mmol, 1 equiv) was placed in a 25 mL Schlenk flask under argon and dissolved in 5 mL of THF. The lithiofluorene solution was cooled to −78 °C, and the allyl bromide solution was cannulated into the reaction mixture. The reaction solution was warmed to room temperature and stirred for 3 h. When GC analysis indicated complete allylation, the reaction solution was cooled again to −78 °C and more 2.5 M *n*-butyllithium (9.7 mL, 24.1 mmol) was added. The solution was warmed to room temperature and stirred for 2 h. It was again cooled to −78 °C, and neat 2,3-dibromopropene (2.5 mL) was added via syringe. The reaction mixture was again warmed to room temperature and stirred for 12 h. When GC analysis indicated essentially quantitative conversion to a single product, most of the THF was removed *in vacuo* and the reaction was quenched with 25 mL of H_2O. The remaining solution was poured into 125 mL of diethyl ether and the organic layer separated. This was

---

[29] Narula, C. K.; Mak, K. T.; Heck, R. F. *J. Org. Chem.* **1983**, *48*, 2792−2796.

[30] Grigg, R.; Stevenson, P.; Worakun, T. *Tetrahedron* **1988**, *44*, 2033−2048.

washed with 25 mL of brine and dried over $MgSO_4$, and the solvents were removed with a rotary evaporator. The resultant yellow oil was dried over CaH_2 and then distilled at full vacuum at 100 °C to give 5.71 g (73% yield) of product. ^1H NMR ($CDCl_3$): δ 2.72 (d, $J = 7.1$ Hz, 2H), 3.20 (s, 2H), 4.82 (m, 3H), 5.08 (d, $J = 1.8$ Hz, 1H), 5.21 (m, 1H), 7.35 (m, 6H), 7.71 (m, 2H). ^{13}C NMR: δ 44.5, 49.0, 54.4, 118.1, 119.9, 120.1, 124.0, 126.8, 127.4, 127.6, 133.0, 140.9, 147.9. Anal. Calcd: C, 70.16; H, 5.27. Found: C, 70.34; H, 5.29.

2-Bromo-1,7-octadiene (1d).[29] The same procedure was used as for **1b**, replacing 4-bromobutene with 5-bromopentene. ^1H NMR ($CDCl_3$): δ 1.41 (m, 2H), 1.57 (m, 2H), 2.08 (m, 2H), 2.42 (t, $J = 7$ Hz, 2H), 4.95 (dd, $J = 2.0$, 11.4 Hz, 1H), 5.10 (dt, $J = 1.6$, 17.0 Hz, 1H), 5.385 (d, $J = 1.5$ Hz, 1H), 5.557 (d, $J = 1.5$ Hz, 1H), 5.81 (m, 1H). ^{13}C NMR: δ 27.6, 27.9, 33.7, 41.5, 114.9, 116.7, 134.9, 138.8.

Stoichiometric Cyclization of 1a To Form 4a. Under nitrogen, a 25 mL Schlenk flask was charged with zirconocene dichloride (146 mg, 0.5 mmol). A second 25 mL Schlenk flask was charged with *N*-allyl-*N*-(2-bromoallyl)aniline (**1a**; (126 mg, 0.5 mmol). After both Schlenk flasks were removed to a vacuum manifold, 3 mL of diethyl ether was added to each flask via cannula. While it was stirred, the zirconocene slurry was cooled to −78 °C; then 0.4 mL of 2.5 M *n*-butyllithium was added via syringe. The resulting yellow solution was stirred at this temperature for 1 h. The aniline solution was then cannulated into the reaction vessel, and the solution was warmed to room temperature over the course of 1 h. The solution turned orange during this time. A 0.2 mL aliquot was removed and quenched with H_2O/ether; GC analysis of the organic phase showed near-complete conversion of starting material. The reaction mixture was quenched by addition of 1.0 mL of D_2O and then stirred for 2 h. The mixture was poured into 30 mL of 1:1 water/ether in a separatory funnel, and the organic layer was separated. The acid-sensitive product was filtered through neutral alumina and then washed with 10 mL of saturated aqueous $NaHCO_3$. The organic layer was separated and dried briefly over $MgSO_4$; then the solvent was removed on a rotary evaporator to afford a white solid (85 mg, 98% yield). ^1H NMR (C_6D_6): δ 0.88 (dd, $J = 4.5$, 1.9 Hz, 2H), 2.525 (m, 2H), 3.24 (m, 1H), 3.58 (d, $J = 13.9$ Hz, 1H), 3.8 (d, $J = 13.7$ Hz, 1H), 4.78 (d, $J = 2.0$ Hz, 1H), 4.81 (d, $J = 2.0$ Hz,1H), 6.49 (d, $J = 8.6$ Hz, 2H), 6.83 (t, $J = 7.3$ Hz, 1H), 7.30 (m, 2H). ^2H NMR: δ 0.88 (s, 1H). ^2H NMR (C_6D_6): δ 0.881 (s). ^{13}C NMR ($CDCl_3$): δ 16.12 (t, $J_{D-C} = 19.5$ Hz), 37.10, 53.12, 55.04, 104.23, 112.35, 116.54, 129.1, 147.9, 151.7.

Stoichiometric Cyclization of 1a To Form 3a. This procedure is identical with that above, with water substituted for D_2O. The product was recrystallized from hexanes as a final step before elemental analysis. ^1H NMR (C_6D_6): δ 0.90 (d, $J = 5.1$ Hz, 2H), 2.525 (m, 2H), 3.24 (m, 1H), 3.58 (d, $J = 13.9$ Hz, 1H), 3.8 (d, $J = 13.0$ Hz, 1H), 4.78 (d, $J = 2.0$ Hz, 1H), 4.81 (d, $J = 2.0$ Hz,1H), 6.49 (d, $J = 7.7$ Hz, 2H), 6.83 (t, $J = 7.3$ Hz, 1H), 7.30 (m, 2H). ^{13}C NMR (C_6D_6): δ 16.12 (t, $J_{D-C} = 19.5$ Hz), 37.10, 53.12, 55.04, 104.23, 112.35, 116.54, 129.1, 147.9, 151.7.

Stoichiometric Cyclization of 1c with Deuterium Quench (4c). This reaction procedure was identical with the cyclization of **1a** in formation of reduced zirconocene and reaction with the substrate. A 1 mmol portion of 9-(3-propenyl)-9-(2-bromo-3-propenyl)fluorene (0.325 g) was used. After the substrate was reacted with the reduced zirconocene for 1 h, a 0.2 mL aliquot was removed and quenched in water/ether and the organic layer used for GC analysis, which indicated 93% conversion of starting material. The cyclized product accounted for 75% of the converted material. The largest minor product accounted for 13% of the converted material and was shown to be 9,9-diallylfluorene by co-GC with authentic material. At this point the reaction mixture was quenched by addition of 1.0 mL of D_2O and then stirred for 3 h. The mixture was poured into 30 mL of 1:1 water/ether, and the organic phase was separated. Filtration of organics through neutral activated alumina was followed by drying over $MgSO_4$. The solvent was removed on a rotary evaporator to afford an off-white semicrystalline solid. Recrystallization from warm toluene afforded needlelike crystals (40 mg). Note that although the ^2H NMR chemical shift is downfield from where it is expected, only the methyl carbon is split as a triplet in the ^{13}C spectrum, indicating that the deuterium is placed only on the pendant methyl group. ^1H NMR ($CDCl_3$): δ 1.29 (d, $J = 6.9$ Hz, 2H), 2.01 (m, 1H), 2.12 (m, 1H), 2.68 (d, $J = 16.2$ Hz, 1H), 3.03 (d, $J = 16.2$ Hz, 1H), 3.15 (m, 1H), 5.05 (dd, $J = 1.8$, 5.9 Hz, 2H), 7.2−7.5 (m, 6H), 7.67−7.73 (m, 2H). ^2H NMR ($CDCl_3$): δ 1.88. ^{13}C NMR: δ 18.93 (t, $J_{D-C} = 19.9$ Hz), 38.3, 45.1, 48.0, 55.4, 105.8, 119.6, 122.6, 123.1,126.8, 126.9, 127.3, 127.4. Anal. Calcd: C, 92.26; H, 7.74. Found: C, 92.02; H, 7.89.

Stoichiometric Cyclization of 1b with Deuterium Quench. The reaction procedure was identical with the cyclization of **1a** in the formation of reduced zirconocene and reaction with the substrate. A 1 mmol portion of 2-bromo-1,6-heptadiene (0.179 g) was used. After 1 h, 1.0 mL of D_2O was added to quench the reaction, and the resulting slurry was stirred for 10 h. The solution was poured into 10 mL of H_2O/10 mL of diethyl ether, and the organics were separated. After filtration through neutral type I alumina, the organics were dried over $MgSO_4$. GC analysis of an aliquot from this solution indicated 98% conversion, with a single peak accounting for 74% of the reaction products. This peak was confirmed to be deuterated 2-methyl-1-methylenecyclopentane by co-GC with authentic 2-methyl-1-methylenecyclopentane (prepared as detailed below). Due to the volatility of the product, isolation of the product from the ethereal solvent proved impossible. Further analysis of the product was performed by ^2H NMR in the ethereal solvent and GC/EIMS. Electron impact MS has the advantage of not only providing data on the highest molecular weight species in the sample but also indicating the molecular weights of fragmentation products. Loss of a methyl radical is the most rapid process for ionized 2-methyl-1-methylenecyclopentane. The deuterated 2-methyl-1-methylenecyclopentane has a mass of 97 amu corresponding to the highest mass peak of significance observed in the spectrum (abundance 340 000). Loss of a monodeuterated methyl radical results in a peak at 81 amu, as is observed (abundance 820 000). However, loss of an undeuterated methyl results in a peak at 82 amu, which is also seen (abundance 680 000). Undeuterated 2-methyl-1-methylenecyclopentane does not exhibit a significant peak at 82 amu (*vide infra*). The simplest explanation for this observed peak is that a significant amount of deuterium is "washed" into the carbocycle via β-hydride elimination/insertion of the zirconium adduct. Furthermore, ^2H NMR analysis was performed on three separate reaction products, each prepared as above. None show the expected chemical shift of 0.9 ppm. ^2H NMR ($CDCl_3$): δ 1.3−1.5 (2 of 3), 1.6−1.8 (all 3), 2.0−2.5 (1 of 3).

Preparation of 2-Methyl-1-methylenecyclopentane (3b) via Wittig Olefination. A 100 mL round-bottom Schlenk flask was charged with NaH (0.36 g, 15 mmol) and 15 mL of DMSO. Hydrogen evolution and a green color were observed as the solution was heated to 60 °C in a water bath. When the color faded to clear and hydrogen evolution ceased, the solution was cooled to room temperature, and methyltriphenylphosphonium iodide was added through an argon stream. The solution immediately turned bright yellow. After the mixture was stirred for 5 h at room temperature, 2-methylcyclopentanone (1.61 mL, 15 mmol) was added via syringe, and the solution was stirred overnight. Analysis of a hydrolyzed aliquot showed near-complete conversion to 2-methyl-1-methylenecyclopentane. The product was carefully vacuum-transferred to a small flask, with pressure always exceeding 0.3 mmHg to avoid DMSO transfer. Whan a visible amount of material had collected, the transfer was halted. Analysis by ^1H NMR and GC show that the collected product is 91.4% pure, with benzene as the main impurity, comprising 7.3% of the remaining material. Mass spectral analysis confirmed the product identity. ^{1}H NMR (CDCl$_3$): δ 0.9 (d, J = 6.7 Hz, 3H), 1.1 (m, 1H), 1.45 (m, 1H), 1.6 (m, 1H), 1.8 (m, 1H), 2.25 (m, 3H), 4.658 (s, 1H), 4.745 (s, 1H). ^{13}C NMR (CDCl$_3$): δ 18.94, 23.89, 32.86, 35.36, 38.71, 103.48, 128.27. EIMS (m/z 96), fw = 96. Significant fragmentation peaks were also observed at 81, 67, and 55 amu.

Stoichiometric Cyclization of 1a with CO Insertion (8a). In a drybox a 50 mL Schlenk flask was charged with zirconocene dichloride (0.292 g, 1 mmol), and a 25 mL Schlenk flask was charged with the aniline substrate **1a** (0.262 g, 1 mmol). The flasks were attached to a vacuum manifold, and 4 mL of toluene was added to each flask. The zirconocene slurry was cooled to −78 °C, and 0.8 mL of 2.5 M *n*-butyllithium in hexanes was added via syringe. After the resulting solution was stirred for 1 h at −78 °C, the aniline solution was added via cannula. The reaction solution was warmed to room temperature over 1 h. The solution was then transferred to another 50 mL Schlenk flask through a cannula filter to remove the lithium chloride. The GC analysis of an aliquot quenched in water/ether showed near-complete conversion of **1a**. Carbon monoxide was bubbled vigorously through the reaction solution for 1.5 h. The solution color changed from orange to clear yellow during this time, and a white precipitate began to form. The remaining toluene was removed in vacuo to afford a light yellow solid. Recrystallization from warm toluene with this material was attempted but afforded only a light yellow precipitate (first batch 86 mg, 17% yield). ^{1}H NMR (C$_6$D$_6$): δ 2.75 (m, 2H), 3.08 (dd, J = 18.6, 5.8 Hz, 1H), 3.14 (m, 1H), 3.35 (dd, J = 9.1, 7.3 Hz, 1H), 3.65 (dd, J = 32, 16 Hz, 2H), 4.78 (d, J = 2.0 Hz, 1H), 4.81 (d, J = 2.0 Hz, 1H), 5.52 (s, 10H), 6.52 (d, J = 7.8 Hz, 2H), 6.85 (t, J = 6.4 Hz, 1H), 7.28 (dd, J = 8.3, 6.4 Hz, 2H). ^{13}C NMR (CDCl$_3$): δ 38.5, 51.3, 52.7, 53.7, 106.8, 109.3, 112.3, 117.0, 121, 129.2, 149.

Catalytic Cyclization of 2-Bromo-1,6-heptadiene (1b) with Deuterium Quench. In the drybox, a 25 mL Schlenk flask was charged with substrate **1b** (0.183 g, 1 mmol) and decane (0.138 g, 1 mmol) as internal standard. A second 25 mL Schlenk flask was charged with zirconocene dichloride (30 mg, 0.1 mmol). The flasks were removed from the box and attached to an argon manifold. A 2.0 mL portion of diethyl ether was added to the heptadiene flask, and 1.0 mL of diethyl ether was added to the zirconocene flask, both via syringe. A 2.0 mL portion of 2.0 M butylmagnesium chloride in ether was then added to the zirconocene flask via syringe at room temperature, and the substrate solution was immediately added to the reaction mixture via a cannula. Occasional monitoring of the reaction was performed by GC analysis of 0.1 mL aliquots quenched in water/ether. The main product had the same resolution time as authentic 2-methyl-1-methylenecyclopentane in co-GC experiments. The reaction was quenched by cooling the flask to 0 °C, slowly adding 1.0 mL of D$_2$O, and then stirring for 2 h. The reaction solution was poured into 20 mL of 1:1 water/ether, the organic layer was separated, washed with saturated aqueous NaHCO$_3$, and poured through neutral alumina. This solution was then used for GC/MS and ^{2}H NMR analysis.

Acknowledgment. This research has been supported by National Science Foundation Grant No. CHE-9522881.

OM960870I