Kinetics and Substituent Effects in the Formation of Zirconocene Thioaldehyde Complexes: β-Hydride Elimination versus Cyclometalation

Stephen L. Buchwald* and Ralph B. Nielsen

Contribution from the Department of Chemistry, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139. *Received August 10, 1987*

Abstract: A variety of zirconocene thioaldehyde complexes **1** have been prepared in high yield by heating (alkylthio)methylzirconocenes **2** in the presence of PMe_3. The formation of the thiobenzaldehyde complex (**1b**) from $Cp_2Zr(Me)SCH_2Ph$ (**2b**) has been found to follow first-order kinetics independent of trimethylphosphine concentration, with $\Delta H^{\ddagger}$ = 18.6 (0.1) kcal/mol and $\Delta S^{\ddagger}$ = −20.6 (0.4) eu. A large primary kinetic isotope effect (k_H/k_D = 5.2 (0.2) at 80 °C) was observed for the transformation. A Hammet plot showed that phenyl substituents exert a modest influence on the reaction rate, with ρ = +0.39 (0.02). These observations are more consistent with a concerted four-center cyclometalation process in which the transition state is polarized so that hydrogen moves as a proton than with a stepwise β-hydride elimination/reductive elimination sequence.

We recently reported the preparation, characterization, and some reactions of trimethylphosphine-stabilized zirconocene thioacetaldehyde (**1a**) and thiobenzaldehyde (**1b**) complexes.[1] These compounds are formed in high yield by thermolysis of the corresponding (alkylthio)methylzirconocene complexes **2** in the presence of trimethylphosphine. The complexes **2** can be prepared by treating chloromethylzirconocene[2a] with a lithium thiolate or by treating dimethylzirconocene[2b] with a thiol.[2c] The reaction of **2** to form **1** appears to be general for thiolate fragments with α-hydrogens. In addition to **1a** with **1b**, we have prepared, isolated, and characterized a variety of para-substituted thiobenzaldehyde complexes **1c–f** (Figure 1). Compounds **1a–f** are yellow crystalline solids, which exhibit ^1H, ^{13}C, and ^{31}P NMR spectra, IR spectra, and elemental analyses that are consistent with the structures shown.

Thioaldehyde complexes of transition metals have attracted a considerable amount of recent interest.[3] Specific attention has been given to synthetic routes to these complexes, structural characterization, the possible application of these complexes to organic synthesis, and the suggestion that the formation of thioaldehyde complexes is involved in the sulfur poisoning of Fischer–Tropsch and related catalysts.[3a,d] Our high-yield preparation of thioaldehyde complexes from thiols and a transition-metal dialkyl is probably the simplest synthesis yet reported,[3] emphasizing that thioaldehyde complexes may indeed be readily formed from simple sulfur-containing compounds on a catalyst surface. We are particularly interested in the mechanism of the formation of **1** from **2**, not only because it is simple and general but also because it is closely related to the formation of early-transition-metal benzyne[4] and alkyne[5] complexes, which are being studied in our laboratory.

Assuming for the moment that the formation of **1** from **2** is an intramolecular process (see discussion below), several possible mechanistic pathways can be outlined, as shown in Figure 2. In pathway A, **2** decomposes via a rate-determining β-hydride elimination to form a hydridomethylzirconocene π-thioaldehyde intermediate **3**. Compound **3** then reductively eliminates[6] methane to form the zirconocene thioaldehyde intermediate **4**, which rapidly associates phosphine to form **1**. Pathway B is identical with A, except that reductive elimination is rate determining and the β-hydride elimination is reversible, resulting in a steady-state concentration of **3** during the course of the reaction. It should be noted that no stabilization of the thioaldehyde fragment through π-back-bonding is possible in a d^0 intermediate such as **3**. Lack of π-back-bonding in an intermediate such as **3**, however, is presumably less critical to the stability of a thioaldehyde ligand than to a benzyne or cyclohexyne ligand.[4,5] Since **2** is also a Zr(IV) d^0 complex, the formation of **3** from **2** would have to involve transfer of hydrogen as a hydride from carbon to zirconium, and electron-releasing R substituents should accelerate this process. The overall reaction kinetics should reflect this if pathway A is operative. If pathway B is operative, any large effect of R on the rate of reductive elimination and formation of **4** from **3** may partially mask the effect of R on the steady-state concentration of **3**. One might suppose, however, that the primary effect of R in the C–H bond-breaking β-hydride elimination would be greater in magnitude than the secondary effect of R on the rate of reductive elimination and that electron-releasing groups should, in general, accelerate a β-hydride elimination/reductive elimination sequence on a d^0 metal.

Pathways C–E all involve concerted, four-center mechanisms, which may be thought of as C–H bond-activation or cyclometalation processes.[7] Pathway C is a synchronous mechanism with little or no charge separation in the transition state. Pathways D and E are concerted asynchronous processes in which the hy-

(1) Buchwald, S. L.; Nielsen, R. B.; Dewan, J. C. *J. Am. Chem. Soc.* **1987**, *109*, 1590.

(2) (a) Wailes, P. C.; Weigold, H.; Bell, A. P. *J. Organomet. Chem.* **1971**, *33*, 181. (b) Rausch, M. D.; Samuel, E. *J. Am. Chem. Soc.* **1973**, *95*, 6263. (c) For typical thiol syntheses, see: Urquhart, G. G.; Gates, J. W.; Connor, R. *Organic Syntheses*; Wiley: New York, 1955; Collect. Vol. III, p 363; Kofod, H. *Organic Syntheses*; Wiley: New York, 1963; Collect. Vol. IV, p 491.

(3) For leading references on thioaldehyde complexes, see: (a) Adams, R. D.; Babin, J. E.; Tasi, M. *Organometallics* **1986**, *5*, 1920. (b) Mayr, A.; McDermott, G. A.; Dorries, A. M.; Holder, A. K.; Fultz, W. C.; Rheingold, A. L. *J. Am. Chem. Soc.* **1986**, *108*, 310. (c) Hofman, L.; Werner, H. *Chem. Ber.* **1985**, *118*, 4229. (d) Buhro, W. E.; Etter, M. S.; Georgiou, S.; Gladysz, J. A.; McCormick, F. B. *Organometallics* **1987**, *6*, 1150. (e) Buhro, W. E.; Patton, A. *T.*; Strouse, C. E.; Gladysz, J. A.; McCormick, F. B.; Etter, M. C. *J. Am. Chem. Soc.* **1983**, *105*, 1057. (f) Hill, A. F.; Roper, W. R.; Waters, J. M.; Wright, A. H. *J. Am. Chem. Soc.* **1983**, *105*, 5939.

(4) Buchwald, S. L.; Watson, B. T.; Huffman, J. C. *J. Am. Chem. Soc.* **1986**, *108*, 7411.

(5) Buchwald, S. L.; Lum, R. T.; Dewan, J. C. *J. Am. Chem. Soc.* **1986**, *108*, 7441. Buchwald, S. L.; Watson, B. T.; Huffman, J. C. *J. Am. Chem. Soc.* **1987**, *109*, 2544.

(6) For mechanistic studies of reductive eliminations, see: (a) Jones, W. D.; Feher, F. J. *J. Am. Chem. Soc.* **1986**, *108*, 4814. (b) Michelin, R. A.; Faglia, S.; Uguagliati, P. *Inorg. Chem.* **1983**, *22*, 1831. (c) Braterman, P. S.; Cross, R. J.; Young, G. B. *J. Chem. Soc., Dalton Trans.* **1977**, 1892. (d) Abis, L.; Sen, A.; Halpern, J. *J. Am. Chem. Soc.* **1978**, *100*, 2915. (e) Halpern, J. *Acc. Chem. Res.* **1982**, *15*, 332. (f) Buchanan, J. M.; Stryker, J. M.; Bergman, R. G. *J. Am. Chem. Soc.* **1986**, *108*, 1537.

(7) For studies of cyclometalations and/or β-hydride/reductive elimination sequences, see: (a) McCarthy, T. J.; Nuzzo, R. G.; Whitesides, G. M. *J. Am. Chem. Soc.* **1981**, *103*, 3396. (b) Moore, S. S.; DiCosimo, R.; Sowinski, A. F.; Whitesides, G. M. *J. Am. Chem. Soc.* **1981**, *103*, 948. (c) DiCosimo, R.; Moore, S. S.; Sowinski, A. F.; Whitesides, G. M. *J. Am. Chem. Soc.* **1982**, *104*, 124. (d) Rothwell, I. P. *Polyhedron* **1985**, *4*, 177. (e) Bruno, J. W.; Marks, T. J.; Day, V. W. *J. Am. Chem. Soc.* **1982**, *104*, 7357. (f) Schock, L. E.; Brock, C. P.; Marks, T. J. *Organometallics* **1987**, *6*, 232. (g) Smith, G. M.; Carpenter, J. D.; Marks, T. J. *J. Am. Chem. Soc.* **1986**, *108*, 6805. (h) Watson, P. L. *J. Am. Chem. Soc.* **1983**, *105*, 6491.

0002-7863/88/1510-3171$01.50/0

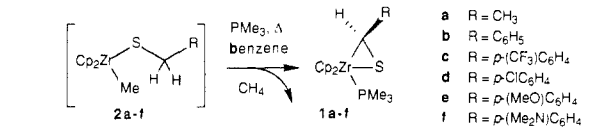

Figure 1.

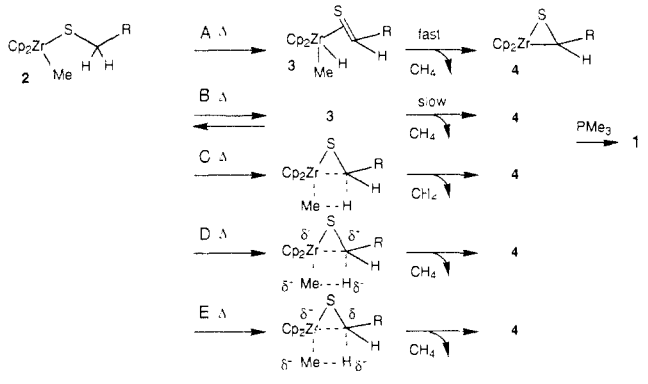

Figure 2.

drogen moves as a hydride or as a proton, respectively. In addition to these concerted processes, stepwise pathways involving ion-pair or radical intermediates are also distinct possibilities.

In order to gain some insight into this reaction, we have determined the kinetic activation parameters and deuterium isotope effect for the formation of the thiobenzaldehyde complex **1b** from **2b**, and we have examined the effects of electron-releasing and -withdrawing para-substituents on the rate of this transformation.

Results and Discussion

The (alkylthio)methylzirconocene complexes **2b–f** were prepared by addition of 1 equiv of the appropriately substituted benzyl mercaptan to a C_6D_6 solution containing 1 equiv of Cp_2ZrMe_2 and 2 equiv of PMe_3. The thiols either are commercially available or are readily prepared by base hydrolysis of the isothiouronium salts, which can be easily prepared from the benzyl halides or benzyl alcohols and thiourea.[2c] After ca. 6 h at 10–20 °C, ^1H NMR evidenced formation of ca. a 90% yield of **2**, contaminated with some Cp_2ZrMe_2 and some dithiolate $Cp_2Zr(SR)_2$. (Attempted purification of the noncrystalline compounds **2** was unsuccessful). Activation parameters for the formation of **1b** and **2b** were determined by heating the C_6D_6 solutions of **2b** in the NMR probe at temperatures between 75 and 90 °C (three samples at each temperature) while the reaction was monitored by ^1H NMR. Both appearance of **1b** and disappearance of **2b** follow first-order kinetics through ca. 6 half-lives ($\tau_{1/2}$ 14.7 min at 80.4 °C). Conversion of **2** to **1** is essentially quantitative, and no ^1H NMR signals corresponding to any intermediate were observed. Activation parameters for the formation of **1b** from **2b** are $\Delta H^\ddagger$ = 18.6 (0.1) kcal/mol and $\Delta S^\ddagger$ = −20.6 (0.4) eu, which correspond to $\Delta G^\ddagger$ = 25.8 kcal/mol at 80.4 °C. A graph of representative first-order rate data and an Arrhenius plot are shown in Figure 3.

The rate of decomposition of **2** is independent of the phosphine concentration in the range studied (0–8 equiv, 0–≈0.6 M). In the absence of trimethylphosphine, heating **2b** results in the formation of methane and several cyclopentadienyl-containing products, which appear to be oligomers of the zirconocene thiobenzaldehyde complex $[Cp_2Zr(HCSPh)]_n$. Treatment of this mixture with PMe_3 leads to very rapid formation of **1b** in undiminished yield (ca. 90% based on Cp_2ZrMe_2, in less than 15 min at 60 °C).

The kinetic isotope effect for the transformation of **2b** to **1b** was determined by monodeuteriated $Cp_2Zr(Me)SCH(D)Ph$ (**2b**) prepared from Cp_2ZrMe_2 and HSCH(D)Ph (greater than 99.5% monolabeled as determined by GC/MS). Heating C_6D_6 solutions of monolabeled **2b** at 80 °C resulted in formation of **1b** in which the ratio of the intensity of the ^1H NMR signals for the thioaldehyde protons to the cyclopentadienyl protons was between

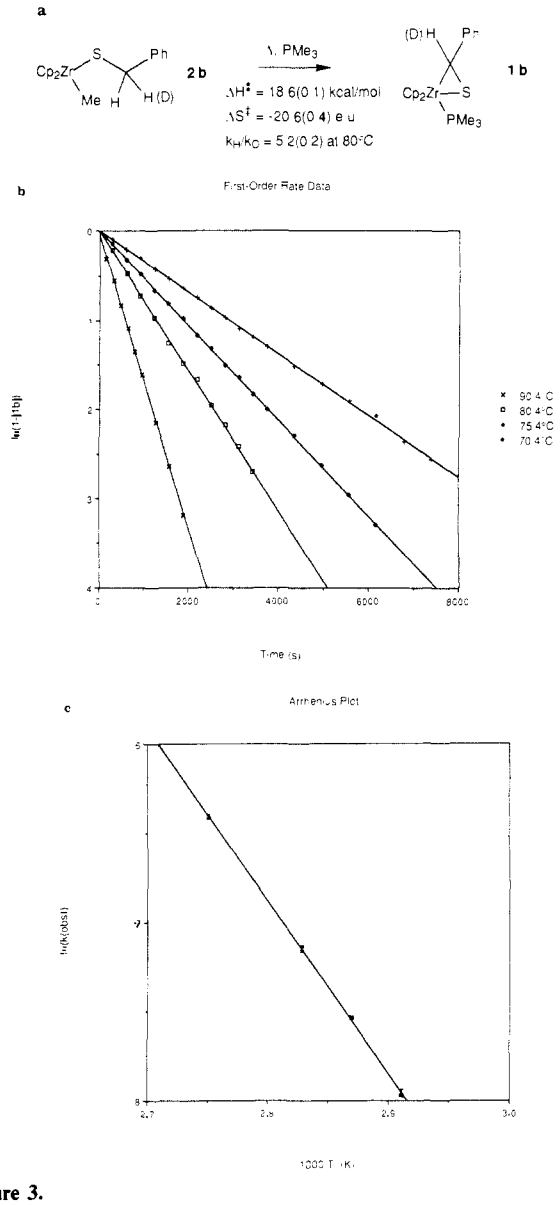

Figure 3.

15.8% and 16.7% of that observed for unlabeled **1b**. This corresponds to a k_H/k_D of 5.2 (0.2) at 80 °C, which extrapolates to a k_H/k_D near 7 at 25 °C, assuming normal Arrhenius behavior.[8]

Heating C_6D_6 solutions of **2b–f** at 75 °C in the NMR probe showed that the transformation is accelerated by the electron-withdrawing substituents (CF_3, Cl) and slowed by electron-releasing substituents (OMe, NMe_2), with ρ = +0.39 (0.02). The Hammet plot is shown in Figure 4.

Several conclusions can be drawn from these results. The first-order behavior observed for the formation of **1b** and **2b** is consistent with a unimolecular process, although the possibility had not been ruled out that a more complicated kinetic scheme is masked by apparent first-order concentration dependence. A double-label experiment, i.e. thermolysis of a mixture of **2b** and deuteriated ($Cp_2Zr(CD_3)SCD_2Ph$) (**2b**), was not attempted because rapid ligand redistribution would presumably scramble the labels before appreciable amounts of **1b** had formed. Evidence for rapid exchange of methyl and thiolate ligands comes from the observation that the cyclopentadienyl ^1H NMR resonances for **2b** and Cp_2ZrMe_2 are coalesced at 80 °C.

The large primary kinetic isotope effect implies that the rate-limiting step involves a transfer of hydrogen. The k_H/k_D value is too large for an equilibrium isotope effect in a fast reversible

(8) Lowry, T. H.; Richardson, K. S. *Mechanism and Theory in Organic Chemistry*, 2nd ed.; Harper & Row: New York, 1981; p 206.

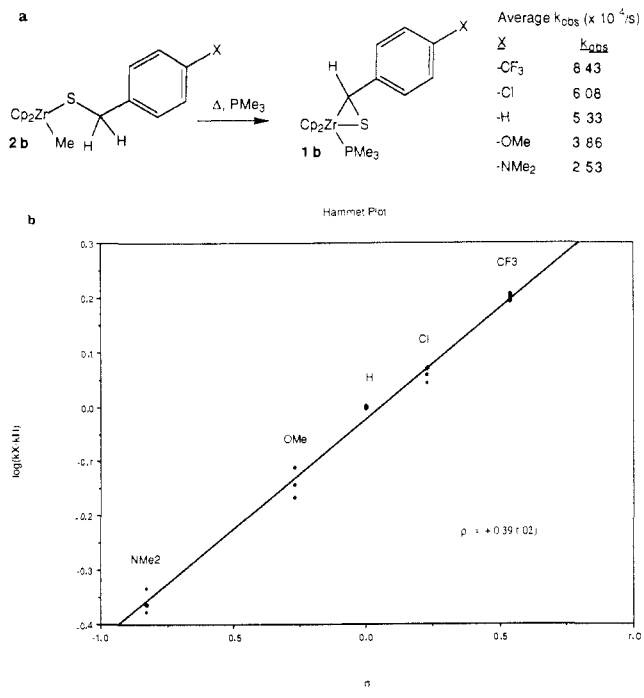

Figure 4.

step before the rate-determining transition state, and it seems impossible to propose a plausible mechanism in which the rate-determining transition state precedes a commitment by the molecule to activate either H or D. This isotope effect is larger than values of 2.0–3.5, which are generally seen for reductive eliminations,[6b,d,7a-b] and examples of inverse isotope effects[6a,f] as small as 0.51 have been seen for some reductive eliminations. It is also larger than the only isotope effect reported for a well-defined β-hydride elimination, for which k_H/k_D is 1.1 at 105 °C.[9] Our k_H/k_D of 5.2 (80 °C) is relatively close to the value of 6.5 (70 °C) reported by Marks[7f] and co-workers for a reaction that is presumed to be an intramolecular C–H bond activation and to the value of 5.5 (70 °C) reported by Watson[7h] for an intermolecular C–H bond activation. These values are near that expected for an idealized C- -H- -C transition state, ignoring tunneling or other quantum mechanical phenomena.[8] The relatively large, negative $\Delta S^{\ddagger}$, indicating an ordered transition state, is more consistent with a rate-determining β-hydride elimination (A) or a concerted mechanism (C–E) than with a rate-determining reductive elimination (B) or a heterolytic or homolytic bond cleavage.

The positive Hammett ρ value, while relatively small, is similar in magnitude but opposite in sign compared to the value of –0.64 (0.12) seen by Bercaw[9] in his study of β-hydride elimination/hydrometalation reactions in the $Cp^*_2Nb(H)$(olefin) system. Bercaw's findings show that β-hydride eliminations, particularly on early transition metals, usually involve movement of hydrogen "as a hydride". The small magnitude of ρ in both cases might be due either to stereoelectronic effects of crowding at the Cp^*_2Nb or Cp_2Zr nucleus, which do not allow for the full effect of the electron density in the aromatic ring to be felt at the benzylic positions, or to the existence of a relatively synchronous concerted mechanism with only a small degree of charge polarization at the transition state. The positive ρ value for the formation of **1** is inconsistent with a rate-determining β-hydride elimination as in pathway A.

While the data do not completely rule out other mechanisms, the simplest mechanism that is consistent with the large isotope effect, the negative entropy of activation, and the positive Hammett ρ value is the four-center concerted process E in which the transition state is slightly polarized so that it resembles the deprotonation of an agostic hydrogen[10] by a methyl group bearing a partial negative charge. This concerted C–H bond-activation process depicted for pathway E is conceptually different from the β-hydride elimination/reductive elimination shown in pathways A or B not only in that there is no metal methyl hydride π-thioaldehyde intermediate with a discrete lifetime but also because there is no direct metal–hydrogen bond formed during the course of the reaction. Concerted mechanisms similar to pathway E have been commonly proposed for C–H bond activations at Lewis acidic d^0 metals such as lanthanides[7h] and actinides,[7e] as well as for activations of distal C–H bonds,[7d] but mechanisms related to A and B have frequently been considered to be plausible alternatives in some cases where β-hydrogens are activated.[7b-d] We feel, however, that such stepwise β-hydride elimination/reductive elimination mechanisms are even less likely in the formation of zirconocene complexes of strained, high-energy species such as benzyne or cyclohexyne[5] than for thioaldehydes, where stabilization through π-back-bonding is presumably less crucial. It appears that such reactions in zirconocene systems are likely to occur by a concerted mechanism. We are continuing work to clarify mechanistic aspects of several related reactions.

Experimental Section

General Procedures. All manipulations, unless otherwise noted, were conducted under nitrogen or argon atmosphere by using standard Schlenk techniques or in a Vacuum Atmospheres Co. drybox. NMR spectra were recorded on Bruker WM-250, Varian XL-300, or Varian XL-400 Fourier transform spectrometers. IR spectra were recorded on an IBM IR/30S Fourier transform spectrometer. Gas chromatography analyses were performed on a Hewlett Packard Model 5890 GC with FID detector using a 25-m capillary column with cross-linked SE-30 as stationary phase. Gas chromatography/mass spectral analyses were obtained with a Hewlett Packard System 5990A GC/MS. Electron impact mass spectra and high-resolution mass determinations (HRMS) were recorded on a Finnegan MAT System 8200. Combustion analyses were performed by Schwarzkopf Microanalytical Laboratory, Woodside, NY.

Benzene, diethyl ether, hexane, benzene-d_6, and toluene-d_8 were distilled or vacuum transferred from sodium/benzophenone ketyl. Cp_2ZrCl_2 was purchased from Boulder Scientific Inc., Mead, CO. (Chloromethyl-*d*)benzene[11] and Cp_2ZrMe_2[2b] were prepared according to literature procedures. All other reagents were available from commercial sources.

Preparation of 1a and 1b. Dimethylzirconocene (2.515 g, 10 mmol) was dissolved in 15 mL of benzene under an argon atmosphere in a 100-mL glass pressure vessel, and trimethylphosphine (2.0 mL, 20 mmol) was added. Ethanethiol (for **1a**, 0.741 mL, 10 mmol), or benzyl mercaptan (for **1b**, 1.174 mL, 10 mmol) dried over 4-Å molecular sieves, was added, and the vessel was sealed. The stirred mixture was maintained at 20 °C for 3 h until methane was no longer evolved, and the yellow solution was then heated to 90 °C for 24 h. Crystals of product formed during the reaction or on cooling the solution to room temperature. The vessel was vented, and 30 mL of hexane was added to precipitate additional product. The solvent was decanted via cannula, and the solid product was washed with 2 × 10 mL of hexane and dried under vacuum.

1a: yield 3.04 g (85%) pale yellow crystals; ^{1}H NMR (300 MHz, C_6D_6) δ 0.94 (d, J_P = 6.3 Hz, 9 H), 2.26 (d, J = 6.3 Hz, 3 H), 3.01 (q, J = 6.3 Hz, 1 H), 5.24 (d, J_P = 1.8 Hz, 5 H), 5.29 (d, J_P = 2.1 Hz, 5 H); $^{13}C\{^1H\}$ NMR (75.4 MHz, C_6D_6) δ 15.60 (d, J_P = 18.5 Hz), 29.86, 39.53 (d, J_P = 5.7 Hz), 104.03, 104.11; $^{31}P\{^1H\}$ NMR (161.9 MHz, C_6D_6, referenced to external 85% H_3PO_4) δ –5.61; IR (KBr) 3073, 2950, 2903, 2836, 1420, 1352, 1304, 1283, 1021, 953, 808, 791, 725, 664 cm^{-1}; high-resolution MS (EI) M^+ for $C_{15}H_{23}PSZr$, calcd 356.0301, found 356.0301 (±0.0005). Anal. ($C_{15}H_{23}PSZr$) C, H. Crystals suitable for X-ray analysis were prepared by slow liquid-phase diffusion of hexane into a benzene solution of **1a**.[1]

1b: yield 3.78 g (90%) bright yellow crystals; ^{1}H NMR (300 MHz, C_6D_6) δ 0.92 (d, J_P = 6.6 Hz, **9** H), 4.18 (s, 1 H), 5.00 (d, J_P = 1.5 Hz, 5 H), 5.27 (d, J_P = 2.1 Hz, 5 H), 7.01 (t, J = 7 Hz, 1 H), 7.36 (t, J = 7 Hz, 2 H), 7.58 (d, J = 7 Hz, 2 H); $^{13}C\{^1H\}$ NMR (100.6 MHz, C_6D_6) δ 15.6 (d, J_P = 18.3 Hz), 47.3 (d, J_P = 7.2 Hz), 104.5, 105.7, 121.6, 156.8 (128.0, 128.3, obscured by C_6D_6 signals except when gated $\{^1H\}$ decou-

(9) Doherty, N. M.; Bercaw, J. E. *J. Am. Chem. Soc.* **1985**, *107*, 2670.

(10) There is no evidence that the β-hydrogens of **2b** are agostic. The ^{1}H NMR spectrum of **2b** remains essentially unchanged at –88 °C in toluene-d_8 solution, the chemical shifts of the benzylic hydrogens of **2b** and monodeuteriated **2b** $Cp_2Zr(Me)SCH(D)Ph$ are essentially identical, and the benzylic C–H coupling constant is a normal value of 138 Hz. See: Brookhart, M.; Green, M. L. H. *J. Organomet. Chem.* **1983**, *395*, 250.

pled); $^{31}P\{^1H\}$ NMR (161.9 MHz, C_6D_6, referenced to external 85% H_3PO_4) δ −4.87; IR (KBr) 3060, 3005, 2967, 2905, 1588, 1481, 1436, 1419, 1304, 1284, 1198, 1169, 1017, 948, 800, 788, 754, 726, 701, 536 cm^{-1}; high-resolution MS (EI) M^+ for $C_{20}H_{25}PSZr$, calcd 418.0458 found 418.0453 (±0.0006), M^+ −76 (**1b** − PMe_3) for $C_{17}H_{16}SZr$, calcd 342.0016, found 342.0015 (±0.0007). Anal. ($C_{20}H_{25}PSZr$) C, H.

Preparation of 1c–f. Dimethylzirconocene (0.252 g, 1 mmol) and trimethylphosphine (0.25 mL, 2.5 mmol) were combined with 2.5 mL of benzene under an argon atmosphere in a 20-mL Schlenk flask with stirring, and the mixture was cooled in an ice/water bath. A total of 1.0 mmol of the appropriate thiol was added via syringe (for **1c**, 0.192 g of *p*-(trifluoromethyl)benzyl mercaptan; **1d**, 0.135 mL of *p*-chlorobenzyl mercaptan (Aldrich); **1e**, 0.145 mL of *p*-methoxybenzyl mercaptan (Aldrich); **1f**, 0.168 g of *p*-(dimethylamino)benzyl mercaptan). The reaction vessel was sealed, and the mixture was stirred at 0–20 °C until methane evolution ceased (ca. 4 h for **1c–e**, 20 h for **1f**). The methane was vented, and the vessel was again sealed. The yellow solution was heated to 85 °C (ca. 4 h for **1c–e**, 8 h for **1f**), the resulting solution was cooled to room temperature, and the volatiles were removed in vacuo. The gummy residue crystallized after either evaporation (**1d**), addition of 2 mL of ether (**1f**), or addition of 2 mL of ether followed by 2 mL of hexane (**1c,e**). The solid was washed at 0 °C with 4 mL of 1:1 ether/hexane and 3 × 2 mL of hexane, and the resulting yellow powder was vacuum dried.

1c: yield 0.372 g (76%) yellow powder; ^1H NMR (300 MHz, C_6D_6) δ 0.89 (d, J_P = 6.6 Hz, 9 H), 3.98 (s, 1 H), 4.90 (d, J_P = 1.5 Hz, 5 H), 5.23 (d, J_P = 1.8 Hz, 5 H), 7.40 (d, J = 7.8 Hz, 2 H), 7.57 (d, J = 7.8 Hz, 2 H); $^{13}C\{^1H\}$ NMR (100.6 MHz, C_6D_6) δ 15.54 (d, J_P = 19 Hz), 46.43 (d, J_P = 5 Hz), 104.64, 105.59, 124.91, 162.02 (some signals are obscured by C_6D_6 signals); $^{31}P\{^1H\}$ NMR (161.9 MHz, C_6D_6, referenced to external 85% H_3PO_4) δ −4.94; ^{19}F NMR (282.2 MHz, referenced to external $CFCl_3$ in C_6D_6) δ −60.69; IR (KBr) 3115, 3047, 2969, 2910, 1603, 1505, 1440, 1421, 1317, 1289, 1284, 1251, 1211, 1172, 1146, 1100, 1061, 1016, 1007, 954, 903, 845, 806, 794 cm^{-1}; high-resolution MS (EI), M^+ for $C_{21}H_{24}F_3PSZr$, calcd 486.0332, found 486.0338 (±0.002). Anal. ($C_{21}H_{24}F_3PSZr$) C, H.

1d: yield 0.360 g (79%) bright yellow powder; ^1H NMR (300 MHz, C_6D_6) δ 0.91 (d, J_P = 6.6 Hz, 9 H), 3.98 (s, 1 H), 4.94 (d, J_P = 2.4 Hz, 5 H), 5.24 (d, J_P = 1.8 Hz, 5 H), 7.31 (m, 4 H); $^{13}C\{^1H\}$ NMR (100.6 MHz, C_6D_6) δ 15.59 (d, J_P = 22 Hz), 46.28 (d, J_P = 5 Hz), 104.61, 105.59, 126.08, 155.79 (some signals are obscured by C_6D_6 signals); $^{31}P\{^1H\}$ NMR (161.9 MHz, C_6D_6, referenced to external 85% H_3PO_4) δ −5.03; IR (KBr) 3111, 2973, 2910, 1560, 1482, 1472, 1437, 1420, 1401, 1305, 1286, 1251, 1199, 1166, 1097, 1082, 1065, 1014, 1005, 948, 888, 831, 792, 725, 709, 669, 647, 621, 532, 444 cm^{-1}. Anal. ($C_{20}H_{24}ClPSZr$) C, H.

1e: yield 0.340 g (76%) yellow powder; ^1H NMR (300 MHz, C_6D_6) δ 0.96 (d, J_P = 6.6 Hz, 9 H), 3.47 (s, 3 H), 4.16 (s, 1 H), 5.05 (d, J_P = 1.5 Hz, 5 H), 5.31 (d, J_P = 1.5 Hz, 5 H), 7.00 (d, J = 9 Hz, 2 H), 7.51 (d, J = 9 Hz, 2 H); $^{13}C\{^1H\}$ NMR (100.6 MHz, C_6D_6) δ 15.66 (d, J_P = 21 Hz), 46.84 (d, J_P = 3 Hz), 54.95, 104.47, 105.65, 113.67, 125.48, 148.81, 155.60; $^{31}P\{^1H\}$ NMR (161.9 MHz, C_6D_6, referenced to external 85% H_3PO_4) δ −4.98; IR (KBr) 3099, 2994, 2965, 2907, 2831, 1498, 1463, 1453, 1440, 1418, 1305, 1287, 1238, 1198, 1176, 1165, 1097, 1021, 947, 905, 798, 724, 690, 668, 631, 559, 539 cm^{-1}. Anal. ($C_{21}H_{27}OPSZr$) C, H.

1f: yield 0.215 g (47%) yellow powder; pure by ^1H NMR; ^1H NMR (300 MHz, C_6D_6) δ 0.98 (d, J_P = 6.3 Hz, 9 H), 2.68 (s, 6 H), 4.24 (s, 1 H), 5.09 (d, J_P = 1.5 Hz, 5 H), 5.33 (d, J_P = 1.8 Hz, 5 H), 6.89 (d, J = 8.4 Hz, 2 H), 7.58 (d, J = 8.4 Hz, 2 H). $^{13}C\{^1H\}$ NMR (100.6 MHz, C_6D_6) δ 15.69 (d, J_P = 19 Hz), 41.52, 47.22 (d, J_P = 8 Hz), 104.39, 105.73, 113.94, 125.43, 145.81, 146.93. $^{31}P\{^1H\}$ NMR (161.9 MHz, C_6D_6, referenced to external 85% H_3PO_4) δ −4.86; IR (KBr) 2908, 1608, 1507, 1479, 1442, 1420, 1330, 1305, 1285, 1199, 1160, 1135, 1057, 1016, 947, 845, 796, 726, 682, 550 cm^{-1}; high-resolution MS (EI), M^+ for $C_{22}H_{30}NPSZr$, calcd 461.0880, found 461.0886 (±0.0009). Anal. ($C_{22}H_{30}NPSZr$) C, H.

^1H NMR Data for Compounds 2a–f: **2a** (250 MHz, C_6D_6) δ 0.07 (s, 3 H), 1.30 (t, J = 7.3 Hz, 3 H), 2.98 (q, J = 7.3 Hz, 2 H), 5.73 (s, 10 H); **2b** (300 MHz, C_6D_6) δ 0.08 (s, 3 H), 4.20 (s, 2 H), 5.73 (s, 10 H), 7.05 (m, 1 H), 7.18 (m, 2 H), 7.37 (m, 2 H); **2c** (300 MHz, C_6D_6) δ 0.06 (s, 3 H), 4.02 (s, 2 H), 5.71 (s, 10 H), 7.18 (d, J = 8 Hz, 2 H), 7.37 (d, J = 8 Hz, 2 H); **2d** (300 MHz, C_6D_6) δ 0.05 (s, 3 H), 4.01 (s, 2 H), 5.71 (s, 10 H), 7.11 (m, 4 H); **2e** (300 MHz, C_6D_6) δ 0.10 (s, 3 H), 3.32 (s, 3 H), 4.21 (s, 2 H), 5.75 (s, 10 H), 6.80 (d, J = 9 Hz, 2 H), 7.29 (d, J = 9 Hz, 2 H); **2f** (300 MHz, C_6D_6) δ 0.13 (s, 3 H), 2.52 (s, 6 H), 4.32 (s, 2 H), 5.76 (s, 10 H), 6.63 (d, J = 8 Hz, 2 H), 7.38 (d, J = 8 Hz, 2 H).

Preparation of Benzenemethane-*d*-thiol. A solution of (chloromethyl-*d*)benzene[11] (2.55 g, 20 mmol) and thiourea (1.52 g, 20 mmol) in absolute ethanol (10 mL) was heated on a steam plate for 12 h. Evaporation of the ethanol yielded a white solid, which was dissolved in 10 mL of water. A solution of 1.2 g of NaOH in 2 mL of water was added, and the mixture was heated on a steam plate for 1.5 h. Acidification with 15% (by volume) H_2SO_4 and extraction with 50 mL of 1:1 ether/pentane and 50 mL of water, drying of the organic layer over $MgSO_4$, evaporation, and Kugelrohr distillation yielded the monolabeled thiol (1.75 g, 70%), which was stored over 3-Å molecular sieves. The material was pure by GC and ^1H NMR. ^1H NMR (300 MHz, $CDCl_3$) δ 1.74 (dt, J = 7.5, 0.9 Hz, 1 H), 3.73 (dt, J = 7.5, 2.3 Hz, 1 H), 7.2–7.4 (m, 5 H); $^{13}C\{^1H\}$ NMR (75.4 MHz, $CDCl_3$) δ 28.66 (t, J = 23 Hz), 127.00, 127.96, 128.65, 141.04.

GC/MS analysis of commercially obtained benzyl mercaptan showed M^+ 124 and the base peak (100%) at m/z 91, with no peak observed at m/z 123 or 90. The monolabeled material gave M^+ 125 and the base peak at m/z 92, with no peaks detected at m/z 124 or 91. Given the apparent detection limit of 0.2%, the material appears to be >99.5% monolabeled.

Preparation of 4-(Trifluoromethyl)benzenemethanethiol. A solution of *p*-$(CF_3)C_6H_4CH_2Br$ (2.39 g, 10 mmol, Aldrich) and thiourea (0.77 g, 10 mmol) in 5 mL of absolute ethanol was refluxed for 2.5 h, and the ethanol was evaporated. The resulting white solid was dissolved in 10 mL of water, a solution of 1.0 g of NaOH in 10 mL of water was added, and the mixture was heated on a steam plate for 1 h. Acidification with 15% (by volume) H_2SO_4, extraction with ether/pentane/water, drying of the organic layer over $MgSO_4$, and evaporation gave the thiol as a clear oil (1.80 g, 94%), pure by GC and ^1H NMR. ^1H NMR (300 MHz, $CDCl_3$) δ 1.79 (t, J = 7.8 Hz, 1 H), 3.78 (d, J = 7.8 Hz, 2 H), 7.43 (d, J = 8.1 Hz, 2 H), 7.58 (d, J = 8.1 Hz, 2 H); $^{13}C\{^1H\}$ NMR (100.6 MHz, $CDCl_3$, multiplicity from $\{^1H\}$ gated decoupling in parentheses) δ 28.49 (t), 124.05 (q, J_F = 269 Hz (s)), 125.54 (q, J_F = 8 Hz (d)), 128.36 (d), 129.26 (q, J_F = 32 Hz (s)), 145.09 (s); IR (neat) 3048, 2939, 1921, 1619, 1417, 1324, 1253, 1165, 1125, 1067, 1020, 954, 844, 754, 687, 613 cm^{-1}; high-resolution MS (EI) M^+ for $C_8H_7F_3S$, calcd 192.0221, found 192.0221 (±0.0007).

Preparation of 4-(Dimethylamino)benzenemethanethiol. Thiourea (1.91 g, 25 mmol) was dissolved in a mixture of 2.5 mL of water and 5.0 mL of 12 N HCl under argon atmosphere. 4-(Dimethylamino)-benzenemethanol (3.78 g, 25 mmol) was added, and the clear solution was stirred 1 h at room temperature and 70 °C for 3 h. The mixture was cooled to room temperature and a solution of 4.1 g of NaOH in 10 mL of water was added. (A light green precipitate of the isothiourea formed.) The suspension was heated to 80 °C and stirred for 30 min, during which time the precipitate dissolved and an oily organic layer formed. The mixture was extracted with 20 mL of ether, and the aqueous layer was titrated to pH 12 with 12 N HCl and extracted with 2 × 30 mL of ether. The ether extracts were dried over $MgSO_4$ and evaporated. The residue was extracted with 2 × 15 mL of hexane; the hexane solution was filtered to remove the insoluble disulfide contaminant. Evaporation of the hexane yielded the thiol as a clear, very pale yellow oil (3.25 g, 73% yield, 97% pure by GC of a dilute benzene solution), which was stored under an inert atmosphere. The thiol in pure form or in concentrated solution, especially in nonpolar solvents, showed considerable reversible formation of a dimeric species, which was observed by GC and NMR: ^1H NMR (300 MHz, $CDCl_3$) major component δ 1.67 (t, J = 7.2 Hz, 1 H), 2.90 (s, 3 H), 3.67 (d, J = 7.2 Hz, 2 H), 6.66 (d, J = 8.4 Hz, 2 H), 7.16 (d, J = 8.4 Hz, 2 H); ^1H NMR minor component δ 1.48 (s, br, 1 H), 2.91 (s, 3 H), 3.55 (s, 2 H), 6.66 (d, J = 8.4 Hz, 2 H), 7.14 (d, J = 8.4 Hz, 2 H); $^{13}C\{^1H\}$ NMR (100.6 MHz, $CDCl_3$, multiplicity from $\{^1H\}$ gated decoupling in parentheses) δ 28.47 (t), 34.96 (t), 40.59 (q), 40.69 (q), 112.60 (d), 112.74 (d), 126.06 (s), 128.71 (d), 128.87 (s), 129.68 (d), 149.56 (s), 149.68 (s); IR (neat) 3073, 2886, 2800, 2559, 1873, 1614, 1566, 1522, 1480, 1444, 1349, 1253, 1226, 1189, 1164, 1130, 1061, 947, 816, 658 cm^{-1}; high-resolution MS (EI) M^+ for $C_9H_{13}NS$, calcd 167.0769, found 167.0770 (±0.0005).

Determination of Kinetic Activation Parameters for the Formation of 1b from 2b. A solution of **2b** was prepared by combining C_6D_6 (6 mL), Cp_2ZrMe_2 (1.26 g, 0.5 mmol), PMe_3 (0.10 mL, 1 mmol), benzyl mercaptan (0.058 mL, 0.5 mmol), and mesitylene (0.020 mL, as internal standard). The solution was maintained at 10–20 °C for 6 h, and then 0.550-mL portions were placed in 5-mm NMR tubes. The thermolyses were carried out in the NMR probe, using a Varian XL-300 NMR spectrometer. Temperatures were calibrated against an ethylene glycol standard sample. Thermolyses of three samples were carried out at each of the temperatures indicated below, and the observed rate constants were determined from the ratio of the cyclopentadienyl signals for the product **1b** to the mesitylene methyl signals. Thermolysis of **2b** at 90 °C in the presence of 8 equiv of PMe_3 showed no measurable difference in the

(11) Kwart, H.; Brechbiel, M. W. *J. Org. Chem.* **1982**, *47*, 461.

Table I

sample label	temp/°C	$\tau_{1/2}$/min	$k_{obsd} \times 10^{-4}$ (σ)/s^{-1}
A	90.4	7.01	16.47 (0.10)
B	90.4	7.00	16.50 (0.21)
C	90.4	6.98	16.54 (0.19)
D	80.4	14.72	7.85 (0.07)
E	80.4	14.64	7.89 (0.13)
F	80.4	14.75	7.83 (0.11)
G	75.4	21.6	5.35 (0.03)
H	75.4	21.8	5.30 (0.03)
I	75.4	21.6	5.34 (0.02)
J	70.4	33.4	3.46 (0.03)
K	70.4	33.5	3.45 (0.02)
L	70.4	32.8	3.52 (0.06)

Table II

substituent	σ	$k_{obsd} \times 10^{-4}$ (σ)/s^{-1}
CF_3	0.54	8.45 (0.22), 8.54 (0.14), 8.29 (0.17)
Cl	0.23	5.89 (0.02), 6.09 (0.08), 6.25 (0.12)
H	0.0	5.35 (0.03), 5.30 (0.03), 5.34 (0.02)
OMe	−0.27	3.64 (0.06), 3.83 (0.03), 4.11 (0.06)
NMe_2	−0.83	2.48 (0.02), 2.25 (0.03), 2.31 (0.04)
ρ = +0.39 (0.02)		

observed rate compared to the thermolyses that employed 2 equiv of phosphine (Table I).

Thermolysis of 2b in the Absence of Trimethylphosphine. An NMR sample of **2b** in C_6D_6 was prepared as above, with no trimethylphosphine, and the sample was heated in the NMR probe to 80.4 °C. The rate of disappearance of **2b** was monitored, using the combined signal of the cyclopentadienyl resonances as an internal standard. The observed rate constant (k_{obsd} = 7.82 (0.09) × 10^{-4}/s) was identical with the rate observed with 2 equiv of PMe_3. The resulting mixture exhibited resonances attributable to methane (δ 0.15 (s)), unreacted Cp_2ZrMe_2 (δ −0.12 (s, 3 H), 5.72 (s, 10 H)), $Cp_2Zr(SCH_2Ph)_2$ (δ 4.20 (s, 4 H), 5.79 (s, 10 H), aryl signals obscured), and zirconocene thiobenzaldehyde oligomers $[Cp_2Zr(HCSPh)]_n$ (δ 3.69, 3.77, 3.83, 4.10 (s, ca. 3:1:3:3 ratio, total of 1 H), 5.28, 5.31, 5.55, 5.57, 5.63, 5.71, 5.94, 5.95 (s, ca. 3:3:3:1:1:3:3:3 ratio, total of 10 H), aryl signals obscured). To this sample was added trimethylphosphine (0.020 mL, ca. 2 equiv), and the tube was heated to 60 °C in the NMR probe. After 15 min, no resonances attributed to oligomeric $[Cp_2Zr(HCSPh)]_n$ remained, and only resonances due to the thiobenzaldehyde trimethylphosphine complex **1b**, Cp_2ZrMe_2, CH_4, free PMe_3, and $Cp_2Zr(SCH_2Ph)_2$ were observed.

Determination of k_H/k_D. Two NMR samples of monodeuteriated **2b** in C_6D_6 containing PMe_3 were prepared as for **2b** above, with the benzenemethane-*d*-thiol prepared above. The samples were heated in an oil bath at 80 °C for 4 h. ^1H NMR showed signals attributable to the thiobenzaldehyde complex **1b**, with a depleted signal for the benzylic hydrogen. The observed signal was 15.82–16.65% of that observed for unlabeled **1b**, using the cyclopentadienyl resonances as an internal standard. This indicates a k_H/k_D of 5.2 (0.2).

Determination of Hammett ρ. NMR samples of **2c–f** in C_6D_6 containing PMe_3 were prepared as for **2b** above, with the appropriate thiol. Observed rate constants for the formation of **1c–f** (three samples for each compound) were measured at 75.4 °C (Table II).

Acknowledgment. We thank the donors of the Petroleum Research Fund, administered by the American Chemical Society, Dr. Alfred Bader, and Firmenich, SA, for support of this work. S.L.B. is the recipient of a Distinguished New Faculty Grant from the Camille & Henry Dreyfus Foundation, Inc., and of a Junior Faculty Research Award from the American Cancer Society, for which he is grateful. R.B.N. is the recipient of a National Science Foundation Predoctoral Fellowship, which is gratefully acknowledged.

Registry No. 1a, 107272-32-2; **1b**, 107272-34-4; **1c**, 113686-33-2; **1d**, 113686-34-3; **1e**, 113686-35-4; **1f**, 113686-36-5; **2a**, 113686-37-6; **2b**, 113686-38-7; **2c**, 113686-39-8; **2d**, 113686-40-1; **2e**, 113686-41-2; **2f**, 113686-42-3; C_6H_5CHDSH, 113686-43-4; *p*-$(CF_3)C_6H_4CH_2SH$, 108499-24-7; *p*-$(Me_2N)C_6H_4CH_2SH$, 113686-44-5; Cp_2ZrMe_2, 12636-72-5; CH_3CH_2SH, 75-08-1; $C_6H_5CH_2SH$, 100-53-8; *p*-$ClC_6H_4CH_SH$, 6258-66-8; *p*-$(MeO)C_6H_4CH_2SH$, 6258-60-2; C_6H_5CHDCl, 79449-94-8; *p*-$(CF_3)C_6H_4CH_2Br$, 402-49-3; *p*-$(Me_2N)C_6H_4CH_2OH$, 1703-46-4.

Synthesis and Reactivity of Binuclear Tropocoronand and Related Organocopper(I) Complexes. Catalytic Enantioselective Conjugate Addition of Grignard Reagents to 2-Cyclohexen-1-one

Gilberto M. Villacorta, Ch. Pulla Rao, and Stephen J. Lippard*

Contribution from the Department of Chemistry, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139. *Received August 13, 1987*

Abstract: The conjugate addition of Grignard reagents, RMgCl, where R = Ph, *n*-Bu, and Me, to 2-cyclohexen-1-one was promoted by a series of new catalysts (0.006–0.04, mol fraction) prepared from copper(I) species and either of two ligand systems. The first used the tropocoronand macrocycle, H_2(TC-5,5), while the second employed a new chiral ligand, H(CHIRAMT), based on *N,N'*-dialkyl-substituted aminotroponeimines. Alkyl-bridged dicopper(I) compounds of both ligands are believed to form in solution, serving as catalysts for the production of racemic 3-substituted cyclohexanones or, in the latter homochiral system, optically active (4–14% ee) products. The regiospecificity, product yield, and enantioselectivity were determined for several reactions utilizing various catalysts. The best results were obtained with copper alkyl complexes freshly prepared in situ. The use of 12-crown-4 as complexing agent for lithium allowed the isolation and characterization of otherwise thermally unstable binuclear copper(I) compounds of the tropocoronands bearing bridged moieties. The structure of one, [Li(12-crown-4)$_2$][Cu_2(μ-Br)(TC-5,5)] (**1**), was determined by X-ray crystallography. Crystal data for $C_{40}H_{62}BrN_4O_8Cu_2Li$ (**1**) is as follows: monoclinic, *Cc*, a = 17.970 (7) Å, b = 16.243 (4) Å, c = 15.660 (6) Å, β = 111.44 (3)°, V = 4254.7 Å^3, Z = 4. The structure was refined to R_1 = 0.043 by using 2122 data with $F_o > 3\sigma(F_o)$. The second compound, [Li(12-crown-4)$_2$][Cu_2(μ-Ph)(TC-5,5)] (**2**), is thought to possess a similar structure on the basis of spectroscopic data and elemental composition. The synthesis and spectroscopic properties (IR, ^1H, and ^{13}C NMR) of the new compounds, including the chiral bidentate ligand, H(CHIRAMT), are reported. A possible catalytic mechanism consistent with the observed reactivity is discussed along with a proposed model for the transition state leading to chiral induction.

Recent work in our laboratory has demonstrated the versatility of tropocoronand, H_2(TC-*n*,*n*'), macrocycles as binucleating ligands.[1-5] These molecules, constructed by linking two aminotroponeimine groups with polymethylene chains to form macro-

0002-7863/88/1510-3175$01.50/0