

Preparation and X-ray structure of a novel chiral methylene bridged titanocene complex [☆]

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Abstract

The synthesis of a novel titanocene complex **2a** containing a cyclopentadienyl and an indenyl ligand is reported. The complex was prepared in a one-pot procedure from indene and pentamethylene fulvene. The preparation and X-ray structure determination of the tetrahydroindenyl analog **2b** is also reported. Catalytic hydrogenation of 2-phenylpyrrolone was conducted with the two complexes. It was found that complex **2b** catalyzed the reaction at a rate of five times that observed for complex **2a**. This rate difference is attributed to the difference in electron density at the metal center.

Keywords: Titanium; Chiral titanocene; X-ray structure

1. Introduction

Group 4 metallocene complexes have long been known to be effective catalysts for olefin polymerization [1]. As such, much effort is devoted to the preparation of novel metallocene derivatives [2]. In addition, Group 4 metallocene complexes have found application as reagents or catalysts for organic reactions [3]. We have recently reported on the use of Brintzinger's *ansa* titanocene complex, ethylene-1,2-bis(η^5 -4,5,6,7-tetrahydro-1-indenyl)titanium-1,1'-binaphth-2,2'-diolate, [4] for the asymmetric reduction of a number of organic compounds. The catalyst has been applied to the asymmetric hydrogenation of imines [5], enamines [6] and olefins [7] as well as the asymmetric hydrosilylation of ketones [8]. In order to further develop catalysts for these reactions we required a flexible method for the synthesis of a variety of titanocene complexes. In this paper we report a one-pot preparation of the novel titanocene complex, **2a**, containing an indenyl and a cyclopentadienyl ligand. Preparation and structural characterization of the tetrahydroindenyl analog **2b** is also reported.

2. Results

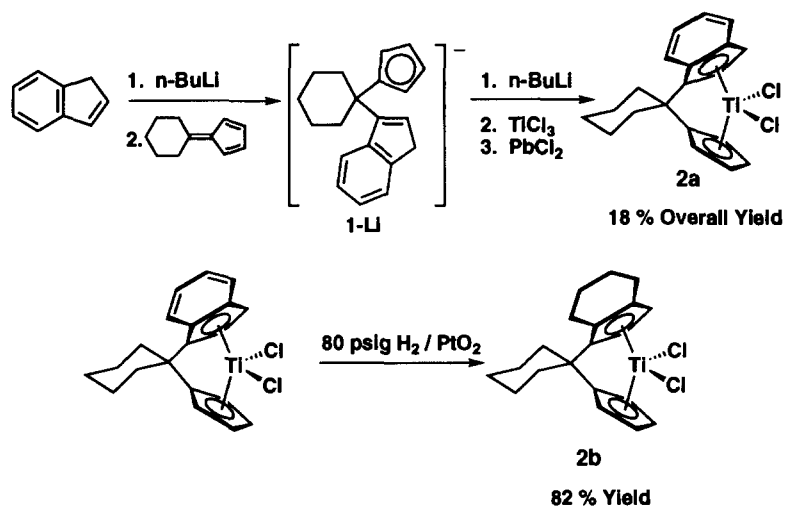
The syntheses of the cyclopentadienyl-indenyl complex **2a** and its saturated derivative **2b** are outlined in Scheme 1. Addition of indenyllithium to pentamethylene fulvene [9] afforded the monolithium salt of the desired ligand framework, **1-Li**. Ligand **1-Li** was converted without isolation, to the dianion, by deprotonation with 1 equivalent of *n*-butyllithium. Treatment of titanium trichloride with the dilithium salt of **1**, followed by oxidation with lead (II) chloride [10] afforded the desired titanocene complex, **2a**, in 18% overall yield (from indene) after recrystallization from toluene. Catalytic hydrogenation of **2a** with PtO₂ at 80 psig of hydrogen afforded the saturated analog **2b**. Pure **2b** was obtained in 82% yield by recrystallization from hot toluene. It is important to note that when the hydrogenation of **2a** was conducted at higher pressures of hydrogen we observed significant decomposition of the complex.

An important issue with regard to the reactivity of metallocene complexes is the steric environment imposed by the cyclopentadienyl ligands. To probe this question an X-ray crystallographic study of complex **2b** was conducted. The ORTEP diagram is shown in Fig. 1 and selected bond distances and bond angles are listed in Table 1.

The complex crystallizes in the space group *Pbca*

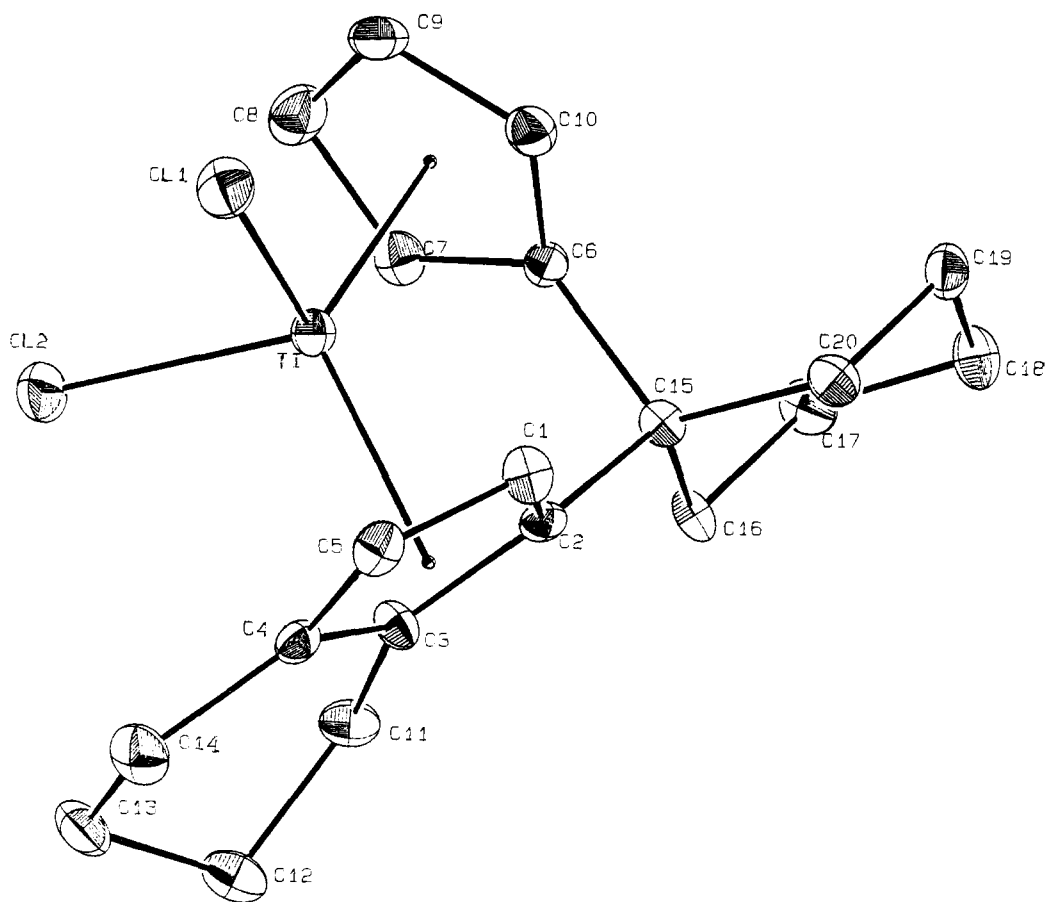
^{*} Corresponding author.

[☆] Dedicated with best regards to our friend Hans-H. Brintzinger in recognition of his myriad contributions to organometallic chemistry on the occasion of his 60th birthday.

Scheme 1. Preparation of complexes **2a** and **2b**.

with one molecule in the orthorhombic unit cell. The bridging cyclohexyl moiety adopts a normal chair conformation with the larger tetrahydroindenyl substituent in the equatorial position. Overall the structure closely resembles that of the methylene bridged bis(cyclopentadienyl) titanium dichloride complex, $\text{CH}_2\text{-(C}_5\text{H}_4)_2\text{TiCl}_2$ [11]. Significant distortion of the geometry

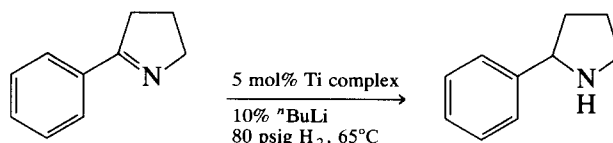
relative to that of titanocene dichloride is observed in complex **2b**. The $\text{C}(6)\text{-C}(15)\text{-C}(2)$ angle is 96.3° , about 13° smaller than that expected for a tetrahedral carbon. The $\text{Cp-Ti-Cp}'$ angle of 121.8° ($\text{Cp} = \text{cyclopentadienyl}$, $\text{Cp}' = \text{tetrahydroindenyl}$) is about 7° less than that of titanocene dichloride [12] indicating an opening of the wedge formed by the two cyclopentadi-

Fig. 1. ORTEP diagram of complex **2b**.

enyl ligands. This is accompanied by a larger Cl(1)–Ti–Cl(2) angle of 97.6°. The Cl–Ti–Cl angle in Cp₂TiCl₂ is 94.4° [12]. The Ti–Cp and Ti–Cp' distances are 2.07 and 2.08 Å respectively. However the metal to ring carbon distances are not equal. The Ti–C distances at the front [C(8) and C(4)] of the complex are longer than those at the bridge [C(6) and C(2)] position by 0.11 Å (for Ti–Cp) and 0.17 Å (for Ti–Cp'). This indicates the strain imposed by the single atom bridge. The Ti–Cl distances of 2.338 and 2.346 are in good agreement with that found for CH₂(C₅H₄)₂TiCl₂. The single atom bridge constrains the two cyclopentadienyl rings in a near eclipsed conformation which causes the C(14) and C(13) atoms of the tetrahydroindenyl ring to project toward the front of the complex. Thus the cyclohexyl portion of the tetrahydroindenyl ligand is positioned to interact with substrates as they approach the metal center.

Attempts to resolve complex **2b** into its enantiomers using the methods developed by Brintzinger for the ethylene bridged bis(tetrahydroindenyl)titanium complex met with limited success. Reaction of complex **2b** with 0.5 equivalents of (*R*)-BINOL in the presence of sodium [4] resulted in formation of only one complex as indicated by ¹H NMR. However we were unable to obtain a pure product from this reaction as decomposition was observed. We also investigated the use of chiral carboxylic acids as resolving agents for complex **2b** [13]. In this case the two diastereomeric titanium complexes were formed as determined by ¹H NMR analysis but no tractable products could be isolated. The instability of these products reflects the increased strain that is imposed by shortening the bridge from two to one carbon atoms.

We examined the catalytic activity of complexes **2a** and **2b** for the hydrogenation of 2-phenylpyrroline (Scheme 2). As can be seen, both complexes catalyzed the hydrogenation with lower reaction rates than our previously reported catalyst system [5]. When complex **2a** was used a *k*_{rel} of 0.11 was obtained, while that for complex **2b** was 0.57. These results are consistent with those reported by Brintzinger for the hydrogenation of olefins using bridged titanocene complexes [14]. Namely, when the number of atoms in the bridge is



Ti complex	turnovers (h)	<i>k</i> _{rel}
EBTHITiCl ₂	2.8	1.00
2a	0.3	0.11
2b	1.6	0.57

EBTHI = ethylene(bis)tetrahydroindenyl

Scheme 2. Hydrogenation of 2-phenylpyrroline with various titanocene complexes.

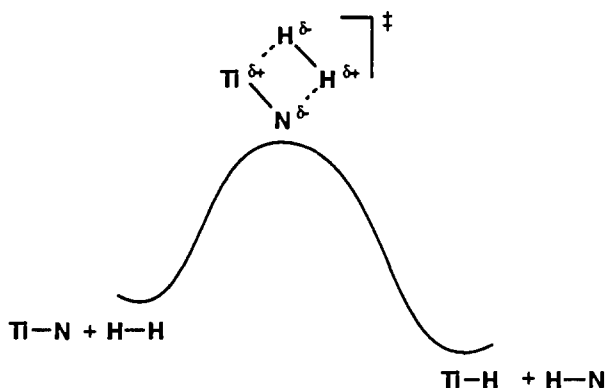
decreased from two to one, lower catalytic activity is observed.

It is informative to compare the reaction rates for complexes **2a** and **2b**. Complex **2b** catalyzed the hydrogenation reaction at a rate of about five times that observed for complex **2a**. While there are subtle steric differences between the two complexes [15], this effect is presumed to be largely electronic. Complex **2a**, which possesses the indenyl ligand, is more electron deficient than complex **2b** which has the more electron donating tetrahydroindenyl ligand. Thus a more electron rich metal center results in an increased reaction rate. We have shown that with the ethylene(bis)tetrahydroindenyl catalyst system the rate limiting step in the imine hydrogenation reaction is hydrogenolysis of the titanium amide intermediate [16]. These results are consistent with activation of dihydrogen via a polar mechanism [17] in the rate limiting transition state (Scheme 3). A more electron rich metal center is expected to lower ΔG^\ddagger in two ways: (1) stabilization of the developing positive charge at the metal center will serve to lower the transition state energy, and (2) more electron donating ligands on the metal will increase the ground state energy of the titanium amide complex. These two effects work in a cooperative fashion to lower the barrier of activation.

In summary, we have prepared a novel titanocene complex in a one-pot procedure. An X-ray structural analysis of complex **2b** indicates that there is significant strain in the molecule. However, the orientation of the

Table 1
Selected bond distances and angles for complex **2b**

Bond distance, (Å)	Bond distance, (Å)	Angle, (°)			
Ti–Cl(1)	2.346(2)	Ti–C(6)	2.336(5)	Cl(1)–Ti–Cl(2)	97.6(1)
Ti–Cl(2)	2.338(2)	Ti–C(7)	2.371(6)	Cp–Ti–Cp'	121.8(1)
Ti–C(1)	2.307(6)	Ti–C(8)	2.455(6)	C(2)–C(15)–C(6)	96.3(4)
Ti–C(2)	2.335(6)	Ti–C(9)	2.444(6)		
Ti–C(3)	2.427(6)	Ti–C(10)	2.349(6)		
Ti–C(4)	2.508(6)	Ti–Cp	2.07(1)		
Ti–C(5)	2.429(6)	Ti–Cp'	2.08(1)		



Scheme 3. Transition state for hydrogenolysis of a titanium amide. The ligands on titanium and the substituents on nitrogen are omitted for clarity.

tetrahydroindenyl ligand is such that substrate–ligand interactions can occur to influence reactions at the metal center. Catalytic hydrogenation of 2-phenylpyrroline using the indenyl complex **2a** and the tetrahydroindenyl complex **2b** indicate that the reaction rates are affected by changing the electronic nature of the complex. The development of novel catalysts with systematically variable steric and electronic properties is currently in progress.

2. Experimental details

All reactions were conducted under an atmosphere of prepurified argon, or hydrogen (grade 5) using standard Schlenk and glove box techniques. Hydrogenation reactions were conducted in a Fisher-Porter Bottle (purchased from Aerosol Lab Equipment, Walton, NY). Nuclear magnetic resonance (NMR) spectra were recorded on a Varian Unity-300, Varian XL-300 or Bruker AC-250 Fourier transform spectrometer. Infrared (IR) spectra were recorded on a Perkin Elmer 1600 series Fourier transform spectrometer. Elemental analyses were performed by Onieda Research Services (Whitesboro, NY) or by Desert Analytics (Tucson, AZ). Tetrahydrofuran (THF) was dried and deoxygenated by refluxing and distilling from sodium/benzophenone ketyl under an argon atmosphere. Methylene chloride was dried by refluxing and distilling from CaH_2 under a nitrogen atmosphere. Catalytic imine hydrogenations using complexes **2a** and **2b** were conducted as described elsewhere [5].

2.1. Preparation of **2a**

A dry Schlenk flask was charged with indene (3.5 ml, 30 mmol) in 60 ml of THF. The solution was cooled to 0°C and *n*-butyllithium (13.2 ml, 36 mmol, 2.72 M in hexanes) was added dropwise via syringe. The orange

solution was warmed to room temperature and stirred for 30 min then cooled to -78°C . A solution of pentamethylene fulvene [9] (4.4 g, 30 mmol) in 30 ml THF was added dropwise via cannula and the resulting mixture was warmed to room temperature and stirred overnight. At this point a small aliquot was removed, quenched with sat. aqueous NH_4Cl and analyzed by capillary GC/MS. Several isomers of the product ($m_w = 262$) were observed totalling 90% of the mixture. The solution was cooled to -78°C and *n*-butyllithium (13.2 ml, 36 mmol, 2.72 M in hexanes) was added. The mixture was warmed to room temperature and transferred to an ice cold suspension of TiCl_3 (4.63 g, 30 mmol) in 300 ml THF. After stirring at room temperature for 4 h the solution was added via cannula to a suspension of PbCl_2 (4.2 g, 15 mmol) in 50 ml THF. The dark green mixture was stirred for 2 h then opened to air and concentrated. The residue was diluted with 400 ml toluene and filtered through celite. The solution was concentrated to ca. 200 ml and cooled to -20°C to afford dark green crystals. The supernatant liquid was decanted and the crystals were dried in vacuo to give 2.04 g (18% yield) of complex **2a**. ^1H NMR (300 MHz, CDCl_3 , TMS): δ 7.66–7.62 (d, 1H, $J = 8.6$ Hz), 7.52–7.45 (m, 2H), 7.22–7.21, (d, 1H, $J = 3.4$ Hz), 7.06–7.0 (m, 1H), 6.77–6.74 (m, 1H), 6.71–6.68 (m, 1H), 5.82–5.80 (d, 1H, $J = 3.5$ Hz), 5.6–5.54 (m, 2H), 2.91–2.84 (m, 1H), 2.62–2.43 (m, 2H), 2.35–2.25 (m, 1H), 1.95–1.85 (m, 4H), 1.79–1.70, (m, 2H); ^{13}C NMR (75 MHz, CDCl_3): δ 136.1, 128.8, 128.7, 127.9, 126.9, 125.5, 124.4, 120.1, 115.8, 111.2, 110.7, 109.3, 98.1, 44.5, 34.2, 33.5, 25.9, 22.3, 21.7; IR (KBr): 3085, 2918, 1443, 1411, 1283, 1220, 1158, 1044, 803, 767, 751, 705, 466; Anal. Calc. for $\text{C}_{20}\text{H}_{20}\text{TiCl}_2$: C; 63.35, H; 5.32, Found: C; 63.35, H; 5.36.

2.2. Preparation of **2b**

A dry Fisher-Porter bottle was charged with complex **2a** (1.11 g, 2.9 mmol), PtO_2 (27 mg, 0.12 mmol) and 50 ml methylene chloride. The vessel was purged with hydrogen ($3 \times$) and pressurized to 80 psig. The resulting solution was stirred at room temperature for 3 h at which time the color had changed from dark green to brown-red. The vessel was vented and opened to air and the mixture was filtered through celite. The crude solid was recrystallized from ca. 30 ml hot toluene. Removal of the supernatant liquid followed by drying in vacuo afforded 0.92 g (82% yield) of complex **2b** as black crystals. ^1H NMR (300 MHz, CDCl_3 , TMS): δ 7.09–7.05 (m, 1H), 6.9–6.86 (m, 1H), 6.55–6.54 (d, 1H, $J = 3.5$ Hz), 5.64–5.61 (m, 1H), 5.53–5.52 (d, 1H, $J = 3.0$ Hz), 5.41–5.38 (m, 1H), 3.14–3.09 (m, 1H), 2.8–2.57 (m, 2H), 2.53–2.43 (m, 5H), 1.57–1.40 (m, 2H); ^{13}C NMR (75 MHz, CDCl_3): δ 142.8, 129.7,

129.3, 128.2, 126.0, 113.8, 113.3, 109.9, 109.3, 108.6, 44.3, 33.8, 32.8, 27.5, 25.9, 25.4, 22.6, 21.9, 21.7, 20.9; IR (KBr): 3081, 2925, 2857, 1637, 1449, 1417, 1346, 1253, 1146, 1079, 1040, 959, 872, 816, 768, 724, 476; Anal. Calc. for $C_{20}H_{24}TiCl_2$: C; 63.28, H; 6.47, Found: C; 62.74, H; 6.19.

2.3. X-ray structure of **2b**

X-ray structure determination of complex **2b** was conducted using a Rigaku-AFC6R diffractometer at 195 K. A total of 4451 reflections were collected. The crystals are orthorhombic, space group *Pbca*; $a = 15.059$, $b = 17.470$, $c = 13.188$, $\alpha = 90.0^\circ$, $\beta = 90.0^\circ$. An empirical absorption correction, using the DIFABS [18] program was applied. Anisotropic refinement was conducted using a combination of the Patterson method and direct methods [19]. The final cycle was based on 1709 reflections and converged with an agreement factor of $R = 0.046$.

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