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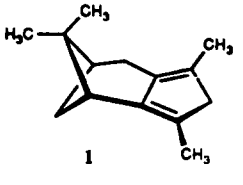
Enantiomerically pure zirconium and hafnium complexes containing a chiral cyclopentadiene derivative prepared from (−)-β-pinene †

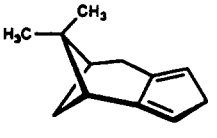
Christophe J. Rousset, Suresh Iyer and Ei-ichi Negishi *
Department of Chemistry, Purdue University, West Lafayette, Indiana 47907, USA

Abstract: Chirally homogeneous (1*S*,8*R*)-3,5,9,9-tetramethyltricyclo[6.1.1.$0^{2,6}$]deca-2,5-diene **1** has been prepared in five steps and 42% overall yield from (−)-β-pinene; its successive treatment first with *n*-BuLi and then with $ZrCl_4$ or $HfCl_4$ provides, in high yields with high π-facial selectivity, the corresponding dichlorobis{η^5-(1*S*,8*R*)-3,5,9,9-tetramethyltricyclo[6.1.1.$0^{2,6}$]deca-3,5-dien-2-yl}zirconium or hafnium, respectively. © 1997 Elsevier Science Ltd. All rights reserved.

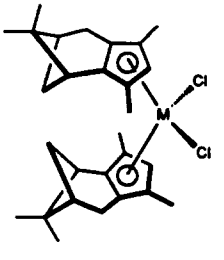
Organometallic compounds containing chiral cyclopentadiene derivatives have recently captured the attention of chemists as a potentially attractive tool for asymmetric transformations.[1] Those that had been prepared earlier (before 1986) mostly contained chiral substituents appended to the cyclopentadiene ring via carbon–carbon single bonds,[2] and their ability to induce asymmetric transformations was generally modest. More recently, considerable efforts have been directed to the synthesis of conformationally more rigid cyclopentadiene derivatives, such as annulated cyclopentadiene derivatives containing cyclic chiral moieties.[3] Some of them, however, are derived from achiral precursors, which necessitates resolution. We hoped to prepare structurally rigid chiral cyclopentadiene derivatives from inexpensive optically active compounds and decided to prepare **1** from β-pinene. This compound is a dimethyl derivative of **2** reported earlier.[3b] One of our hopes was to prepare chiral derivatives of Cp_2MX_2, where M=Ti, Zr, or Hf and X=halogen, which would be very resistant to loss of chirality due to helicity. The presence of the two methyl groups in **1** was thought to significantly slow down this undesirable process. In this paper, we report (i) the synthesis of **1** from (−)-β-pinene and (ii) the synthesis of $Cp_2^*ZrCl_2$ (**3**) and $Cp_2^*HfCl_2$ (**4**), where Cp^* is the deprotonated anion of **1** (Scheme 1).



1



2



3 (M=Zr) **4** (M=Hf)

Scheme 1.

The synthesis of **1** started with commercially available, optically pure (>98%) (−)-β-pinene **5** which was converted to (+)-nopinone **6** via ozonolysis (70%)[4a] or alternatively via ruthenium tetroxide-catalyzed oxidation with $NaIO_4$ (85%).[4b] Treatment of **6** with morpholine in refluxing benzene

† This paper is dedicated to Professor Herbert C. Brown on the occasion of his 85th birthday in recognition of his pioneering and gargantuan contribution to the pinene-based asymmetric synthetic methodology.

* Corresponding author. Email: negishi@chem.purdue.edu

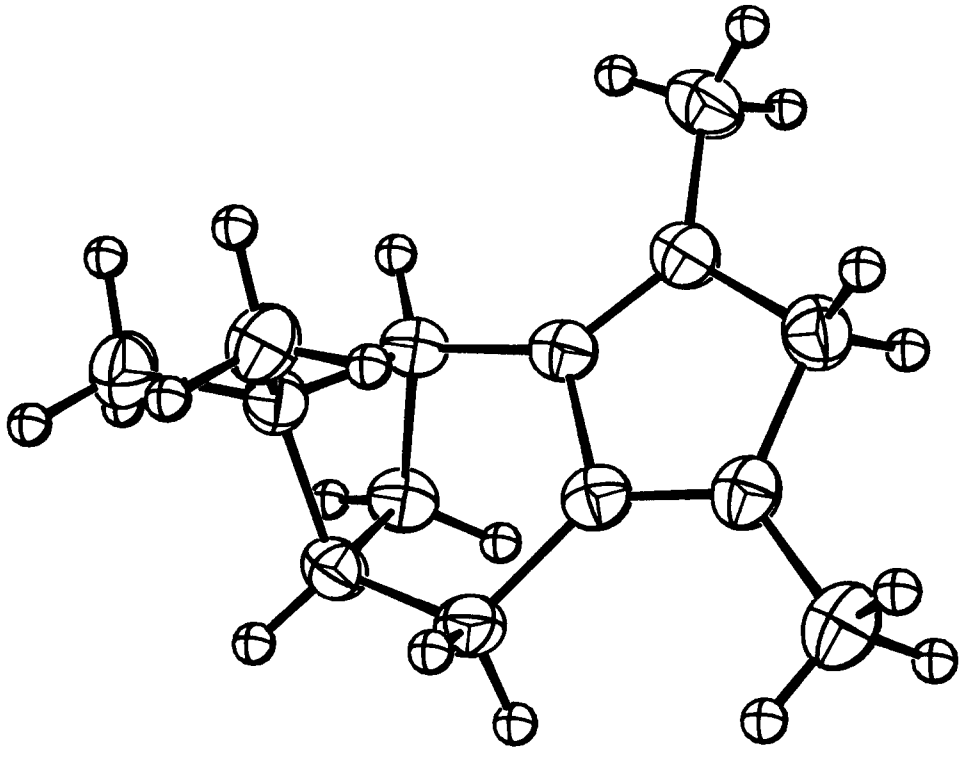
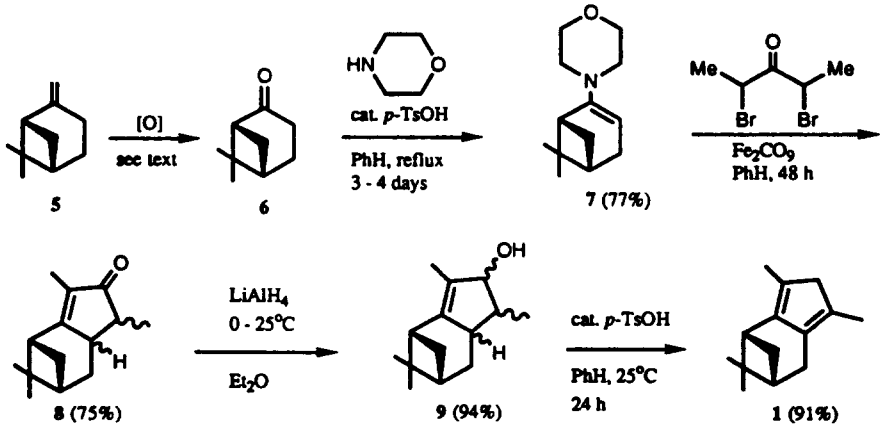


Figure 1. X-Ray ORTEP diagram of **1**.

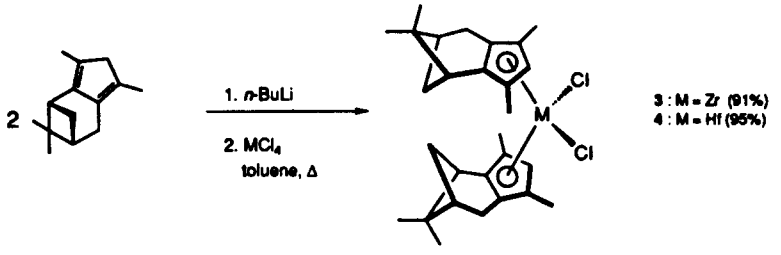
provided the corresponding enamine **7** (77%)[5] which was converted to the bicyclic enone **8** (75%) via the Noyori annulation.[6] Reduction with $LiAlH_4$ in ether resulted in the formation of **9** (94%) which was dehydrated in benzene in the presence of *p*-TsOH to provide **1** (91%). Its X-ray ORTEP diagram is shown in Figure 1. Using the $NaIO_4$–$RuCl_3$ oxidation reaction, **1** has been prepared from **5** in 5 steps and in 42% overall yield (Scheme 2).



Scheme 2.

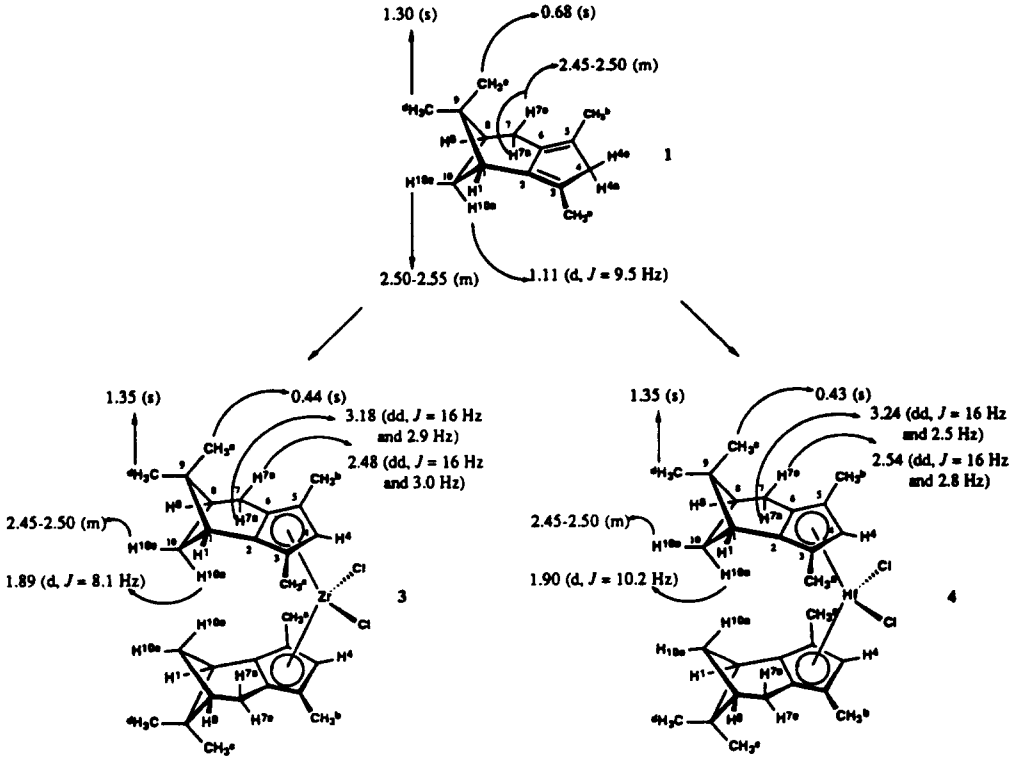
Treatment of the anion of **1**, prepared by the reaction of **1** with *n*-BuLi (1.0 equiv) in refluxing

ether–hexane for 14 h, with zirconium or hafnium chloride (0.5 equiv) in refluxing toluene for 3 days provided the desired metallocene dichloride complexes **3** (91%) and **4** (95%), respectively (Scheme 3).



Scheme 3.

Although **3** and **4** were crystalline (4:1 CH_2Cl_2 and hexane), their X-ray analysis has not been successful. However, their detailed NMR examination indicates that both **3** and **4** are single stereoisomers, in which the geminal dimethyl groups are all on the outside as determined by comparing their ^1H NMR spectra with that of **1**. Indeed, as in some related molecules,[3d,g,h] the metal, i.e., Zr or Hf, exerts a strong deshielding influence on those atoms that are *endo* and *syn* to the metal, i.e., H^{7a} and H^{10a} and a shielding influence on $CH_3{}^C$ (long range anisotropy effect). Their diastereotopic counterparts, i.e., H^{7e}, H^{10e} and $CH_3{}^d$, are little affected (Scheme 4).



Scheme 4.

Experimental section

(1R)-(+)-Nopinone ***6***

A flask was charged with 0.8 L of carbon tetrachloride, 0.8 L of acetonitrile, 1.2 L of water, 54.4 g (400 mmol) of (1*S*)-(−)-β-pinene, and 180 g (840 mmol) of sodium metaperiodate. To this mixture was slowly added ruthenium trichloride hydrate (1.85 g, 8.9 mol) at 25°C.[4b] After stirring the reaction mixture vigorously for 14 h at 25°C, 3.0 L of CH_2Cl_2 was added, and the phases were separated. The upper aqueous phase was extracted 3 times with CH_2Cl_2 and the combined organic extracts were dried over $MgSO_4$. Concentration followed by distillation provided 46.9 g (85%) of the title compound:[4a] bp 106°C (3 mmHg); ^{1}H NMR ($CDCl_3$, Me_4Si) δ 0.85 (s, 3 H), 1.33 (s, 3 H), 1.58 (d, *J*=10 Hz, 1 H), 1.9–2.15 (m, 2 H), 2.2–2.4 (m, 2 H), 2.5–2.65 (m, 3 H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 20.40, 21.08, 24.17, 24.93, 31.71, 39.45, 40.11, 56.84, 212.55; IR (neat) 1710 cm^{-1} (s).

(1R)-(+)-Nopinone morpholine enamine ***7***

(1*R*)-(+)-Nopinone (15.9 g, 115 mmol) was refluxed in benzene (40 mL) with morpholine (20.1 mL, 230 mmol) and *p*-TsOH (2.18 g, 11.5 mmol).[5] After 3–4 days, the reaction mixture was cooled to 25°C. Concentration followed by distillation provided 18.5 g (77%) of the desired product: bp 106°C (3 mmHg); ^{1}H NMR ($CDCl_3$, Me_4Si) δ 0.87 (s, 3 H), 1.24 (d, *J*=9 Hz, 1 H), 1.29 (s, 3 H), 2.05–2.4 (m, 5 H), 2.7–2.8 (m, 4 H), 3.65–3.75 (m, 4 H), 4.41 (s, 1 H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 20.96, 25.94, 29.01, 30.94, 37.82, 40.59, 43.49, 48.77, 66.41, 95.14, 155.64; IR (neat) 1630 (s), 1150 (s) cm^{-1}.

2,4-Dibromopentan-3-one[7]

3-Pentanone (34.4 g, 400 mmol) was mixed with 48% hydrobromic acid (40 mL) and chilled with ice–water. Bromine (41.2 mL, 800 mmol) was added slowly, and the reaction mixture was stirred for an additional 30 min. After addition of water (80 mL), the heavier organic layer was washed with sodium bisulfite and dried over $CaCl_2$. Concentration followed by distillation provided 77 g (79%) of the title compound as a ca. 1:1 diastereomeric mixture: bp 60–62°C (4 mmHg); ^{1}H NMR ($CDCl_3$, Me_4Si) δ 1.80 and 1.86 (2d, *J*=7 Hz, 6 H), 4.80 and 5.00 (2q, *J*=7 Hz, 2 H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 19.35 (21.48), 43.68 (43.89), 195.53 (197.80); IR (neat) 1710 (s) cm^{-1}.

(1R,8S)-3,5,9,9-Tetramethyltricyclo[6.1.1.0^{2,6}]dec-2-en-4-one ***8***

A mixture of $Fe_2(CO)_9$ (14.45 g, 39.7 mmol), **7** (37.72 g, 66.3 mmol), and 2,4-dibromopentan-3-one (8.05 g, 33.1 mmol) was stirred in benzene (150 mL) at 25°C for 40 h.[6] The reaction mixture was then treated with 3% ethanolic NaOH solution (50 mL) at room temperature for 30 min, diluted with water, extracted with ethyl acetate, washed with $NaHCO_3$, brine, and dried over $MgSO_4$. Concentration followed by distillation provided 5.06 g (75%) of the title compound as essentially a single stereoisomer: bp 96°C (1.2 mmHg); ^{1}H NMR ($CDCl_3$, Me_4Si) δ 0.93 (d, *J*=7 Hz, 1 H), 1.11 (s, 3 H), 1.21 (d, *J*=7 Hz, 3 H), 1.41 (s, 3 H), 1.62 (s, 3 H), 1.7–1.8 (m, 1 H), 2.05–2.15 (m, 1 H), 2.15–2.25 (m, 1 H), 2.35–2.5 (m, 1 H), 2.8–3.0 (m, 2 H), 3.17 (t, *J*=6 Hz, 1 H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 7.35, 12.95, 23.12, 27.25, 31.68, 37.29, 39.69, 42.67, 43.60, 46.73, 52.18, 128.34, 179.62, 209.41. IR (neat) 1690, 1695 cm^{-1}.

(1R,8S)-3,5,9,9-Tetramethyltricyclo[6.1.1.0^{2,6}]dec-2-en-4-ol ***9***

To $LiAlH_4$ (1.0 M in Et_2O, 10 mL, 10 mmol) was added (1*S*,8*R*)-3,5,9,9-tetramethyl tricyclo[6.1.1.0^{2,6}]dec-2-en-4-one (8.16 g, 40 mmol) in ether (40 mL) dropwise at 0°C. The reaction mixture was warmed to 25°C and stirred at this temperature for 3 h. The reaction mixture was quenched carefully with 3 N HCl, washed with $NaHCO_3$ and brine, and dried over $MgSO_4$. Concentration provided 7.9 g (94%) of the title compound as essentially a single stereoisomer: ^{1}H NMR ($CDCl_3$, Me_4Si) δ 0.88 (d, *J*=9 Hz, 1 H), 0.96 (s, 3 H), 1.16 (d, *J*=7 Hz, 3 H), 1.30 (s, 3 H), 1.4–1.55 (m, 2 H), 1.58 (d, *J*=1 Hz, 3 H), 2.0–2.10 (m, 1 H), 2.1–2.2 (m, 2 H), 2.45–2.55 (m, 1 H), 2.55–2.65 (m, 1 H), 2.71 (t, *J*=6 Hz, 1 H), 4.1–4.2 (bs, 1 H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 9.79, 14.95, 23.27, 27.54, 31.60, 37.20, 39.55, 43.29, 43.94, 44.05, 56.35, 85.60, 127.69, 146.56. IR (neat) 3100–3600 (b,s) cm^{-1}.

(1R,8S)-3,5,9,9-Tetramethyltricyclo[6.1.1.0^{2,6}]deca-2,5-diene 1

A flask was charged with (1*S*,8*R*)-3,5,9,9-tetramethyltricyclo[6.1.1.0]dec-2-en-4-ol (4.80 g, 23.3 mmol), *p*-TsOH (0.31 g, 1.6 mmol) and benzene (25 mL). The reaction mixture was stirred for 24 h at 25°C, neutralized with K_2CO_3, and dried over $MgSO_4$. Concentration followed by purification by flash chromatography (pentane) afforded 3.98 g (91%) of the title compound which was recrystallized from hexane at low temperature: mp 74–76°C; $[\alpha]_D^{25}$ 134 (c 1, hexane); ^{1}H NMR ($CDCl_3$, Me_4Si) δ 0.68 (s, 3 H), 1.11 (d, *J*=9.5 Hz, 1 H), 1.30 (s, 3 H), 1.80 (s, 3 H), 1.85 (s, 3 H), 2.0–2.1 (m, 1 H), 2.45–2.5 (m, 2 H), 2.5–2.55 (m, 1 H), 2.63 (t, *J*=5.4 Hz, 1 H), 2.80 (bs, 2 H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 12.52, 13.22, 21.65, 26.54, 26.91, 32.18, 40.10, 41.17, 49.21, 126.08, 130.92, 135.27, 144.98. IR (neat) 1635 (w), 1670 (w) cm^{-1}. High resolution MS Calcd for $C_{14}H_{20}$: 188.1565; Found: 188.1560.

The tricyclic diene **1** crystallized in the orthorhombic space group $P2_12_12_1$ (N° 19) with cell dimensions, aα 7.9448(4) Å, bα 8.7254(7) Å, cα 17.393(2) Å, and V=1137.5(3) Å^3 with Z=4 and d(Calcd)=1.100 g cm^{-3}. The data collection was performed with MoK_α radiation (λ=0.71073 Å) on an Enraf–Nonius CAD4 automated diffractometer. The structure was solved using the Patterson heavy atom method and refined in full-matrix least-squares to a conventional R factor of 0.037 (R_w=0.051; GOF=1.540) by using 1316 data, where t>3σ(I), against 207 variables.

Bis(η^5-(1R,8S)-3,5,9,9-tetramethyltricyclo[6.1.10^{2,6}]deca-3,5-dien-2-yl)dichlorozirconium 3

To a solution of (1*S*,8*R*)-3,5,9,9-tetramethyltricyclo[6.1.1.0^{2,6}]deca-2,5-diene **1** (0.432 g, 2.3 mmol) in Et_2O (10 mL) was added *n*-BuLi in hexane (2.35 M, 0.98 mL, 2.3 mmol) at 25°C. The reaction mixture was refluxed for 14 h, cooled to 25°C, and transferred to a mixture of $ZrCl_4$ (0.233 g, 1 mmol) and toluene (50 mL) at −79°C. The reaction mixture was warmed to 25°C and refluxed for 3 days. At this time, TLC indicated the total consumption of **1**. The reaction mixture was evaporated, treated with 3 N HCl (2 mL) and CH_2Cl_2, and stirred for 1 h at 25°C. The aqueous layer was extracted with CH_2Cl_2, and the combined organic layers were dried over $CaCl_2$. Concentration provided 0.509 g (95%) of the crude title compound which was recrystallized from CH_2Cl_2 and hexane (ca. 4:1): mp 185–190°C; $[\alpha]_D^{25}$ 183 (c 0.4, CH_2Cl_2); ^{1}H NMR ($CDCl_3$, Me_4Si) δ 0.44 (s, 3 H), 1.35 (s, 3 H), 1.86 (s, 3 H), 1.89 (d, *J*=8.1 Hz, 1 H), 1.90 (s, 3 H), 2.15–2.2 (m, 1 H), 2.45–2.5 (m, 1 H), 2.48 (dd, *J*=16 and 3 Hz, 1 H), 2.73 (5, *J*=5.4 Hz, 1 H), 3.18 (dd, *J*=16 and 2.9 Hz, 1 H), 5.88 (s, 1 H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 12.88, 13.26, 21.18, 26.14, 27.13, 31.15, 40.43, 40.78, 42.31, 108.91, 114.10, 120.37, 132.32, 142.51. High Resolution MS Calcd. For $C_{28}H_{38}ZrCl_2$: 534.1394; Found: 534.1384.

Bis(η^5-(1R,8S)-3,5,9,9-tetramethyltricyclo[6.1.1.0^{2,6}]deca-3,5-dien-2-yl)dichlorohafnium 4

To a solution of (1*S*,8*R*)-3,5,9,9-tetramethyltricyclo[6.1.1.0^{2,6}]deca-2,5-diene **1** (0.446 g, 2.37 mmol), in Et_2O (10 mL) was added *n*-BuLi in hexane (2.3 M, 1.08 mL, 2.48 mmol) at 25°C. The reaction mixture was refluxed for 14 h, cooled to 25°C, and transferred to a solution of $HfCl_4$ (0.320 g, 1 mmol) in toluene (50 mL) at −78°C. The reaction mixture was warmed to 25°C and heated at reflux for 3 days. At this time, TLC indicated the total consumption of **1**. The reaction mixture was evaporated, treated with 3 N HCl (2 mL) and CH_2Cl_2, and stirred for 1 h at 25°C. The aqueous layer was extracted with CH_2Cl_2, and the combined organic layers were dried over $CaCl_2$. Concentration provided 0.568 g (91%) of the title compound which was recrystallized from CH_2Cl_2 and hexane (ca. 4:1): mp 230–235°C; $[\alpha]_D^{25}$ 208 (c 0.8, CH_2Cl_2); ^{1}H NMR ($CDCl_3$, Me_4Si) δ 0.43 (s, 3 H), 1.35 (s, 3 H), 1.9 (d, *J*=10.2 Hz, 1 H), 1.92 (s, 3 H), 1.97 (s, 3 H), 2.15–2.2 (m, 1 H), 2.4–2.5 (m, 1 H), 2.54 (dd, *J*=16 and 2.5 Hz, 1 H), 2.70 (5, *J*=5.4 Hz, 1 H), 3.24 (dd, *J*=16 Hz and 2.8 Hz, 1 H), 5.75 (s, 1 H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 12.69, 13.02, 21.25, 26.10, 26.84, 30.86, 40.51, 40.66, 42.35, 108.93, 111.44, 118.12, 130.67, 140.52. High resolution MS Calcd for $C_{28}H_{38}HfCl_2$: 620.1767; Found: 620.1766 (lowest isotope ^{176}Hf).

Acknowledgements

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