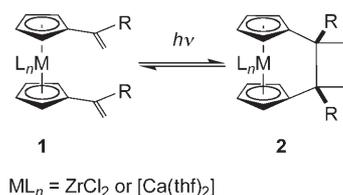


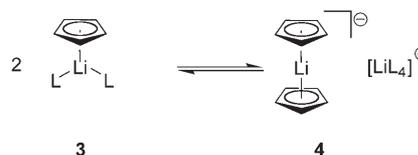
chemistry at the stage of the active organolithium nucleophiles is virtually nonexistent.^[2] All the desired structural and functional-group variations, therefore, need to be made in synthetic sequences either before or after the organolithium stage.^[3] This is also true for syntheses that involve substituted or functionalized lithium cyclopentadienide reagents. Derivatization of cyclopentadienyl (Cp) ligand frameworks in metallocene syntheses, for example, practically never takes place at the stage of the cyclopentadienyllithium reagent; it is mostly done prior to the actual lithiation step or in some rarer cases after the final transmetalation.^[4] We have now found a useful method for carrying out organic functional-group chemistry at the stage of suitably substituted lithium cyclopentadienides. This method demonstrates the principal feasibility of utilizing organic functional-group transformations at active organolithium nucleophiles and at the same time provides a new entry to the synthesis of very useful organic ligand systems.

In our work we focused on the photochemical [2+2] cycloaddition reaction between alkenyl substituents attached to the lithium cyclopentadienides. We had previously shown that the intramolecular [2+2] cycloaddition reaction of bis(alkenylcyclopentadienyl) ligands complexed to Group 4 metals constitutes a viable synthetic pathway to ansa metallocenes.^[5] It had been demonstrated that this reaction could even be extended to the construction of ansa calcocenes and related systems (Scheme 1).^[6,7] Since it was known that



Scheme 1.

lithium cyclopentadienides undergo facile ligand disproportionation of the donor-ligand-stabilized monomer to give the corresponding anionic lithiocene structures (Scheme 2),^[8,9]



Scheme 2.

we decided to use this feature to extend the typical metallocene photocycloaddition reaction to the corresponding alkenyl-functionalized lithiocenes.

We synthesized a series of lithium (alkenyl)cyclopentadienides by means of the fulvene route.^[10] As a typical example *tert*-butylcyclopentadiene (**5e**) was treated with acetone in the presence of pyrrolidine^[11] to yield the 3-*tert*-butyl-substituted 6,6-dimethylpentafulvene **6e**, which was

Organolithium Compounds

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Functional-Group Chemistry of Organolithium Compounds: Photochemical [2+2] Cycloaddition of Alkenyl-Substituted Lithium Cyclopentadienides**

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Organolithium compounds are among the most important reagents in organic and organometallic synthesis.^[1] Because of their high reactivity and sensitivity, functional-group

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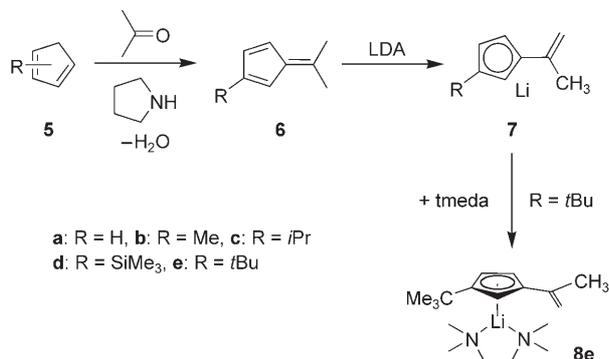
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then treated with lithium diisopropylamide (LDA) in diethyl ether to cleanly yield **7e** in 78% yield (Scheme 3). The (alkenyl-Cp)-Li compound **7e** was characterized spectroscopically and by C,H elemental analysis. Treatment with



Scheme 3.

tetramethylethylenediamine (tmeda) gave [[(H₂C=C-Me)C₅H₃(*t*Bu)]Li(tmeda)] (**8e**), which was characterized by an X-ray crystal structure analysis (see Figure 1, for details

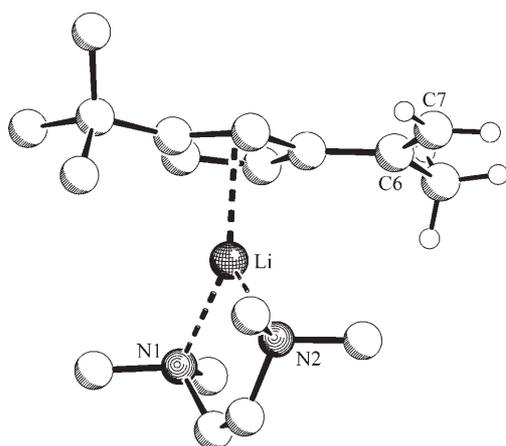


Figure 1. X-ray crystal structure of **8e**.

see the Supporting Information). It features a monomeric structure in which the C=C bond of the alkenyl substituent ($d(\text{C6}-\text{C7})=1.332(4)$ Å) is coplanar with the central 1,3-disubstituted Cp ring. The electrostatic Li-Cp interaction results in uniform ($\eta^5\text{-C}_5\text{H}_3\text{R}^1\text{R}^2$)Li coordination with Li-C distances being in a narrow range between 2.257(5) Å and 2.299(5) Å. The Li-N bond lengths are slightly shorter at 2.125(5) Å (Li-N2) and 2.155(4) Å (Li-N1).^[12]

The lithiocene equilibration can best be monitored by temperature-dependent ⁷Li NMR spectroscopy.^[8] A solution of **7e** in [D₈]THF at ambient temperature features a single sharp resonance at $\delta = -7.5$ ppm. Upon cooling the sample, the signal rapidly broadens and splits into two

broad resonances of almost equal intensity at $\delta = -12.2$ and -12.3 ppm (at 168 K), which we attribute to a mixture of the diastereomeric lithiocenes *rac*-**9e** and *meso*-**9e**. The very broad low-field signal stays broad for a much larger temperature range. It decreases in intensity with decreasing temperature and shifts its maximum continuously to lower field. At the lowest temperature (168 K) a single slightly broadened ⁷Li NMR resonance remains at $\delta = -1.1$ ppm which is approximately equal in intensity to the pair of signals at $\delta = -12.2/12.3$ ppm (see Figure 2). The interpretation of this typical

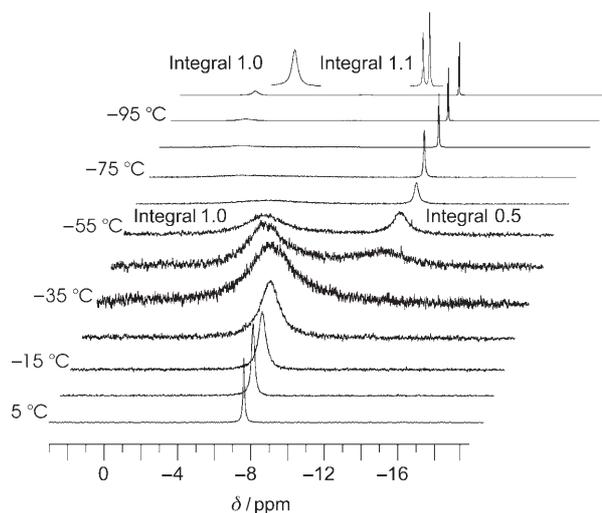
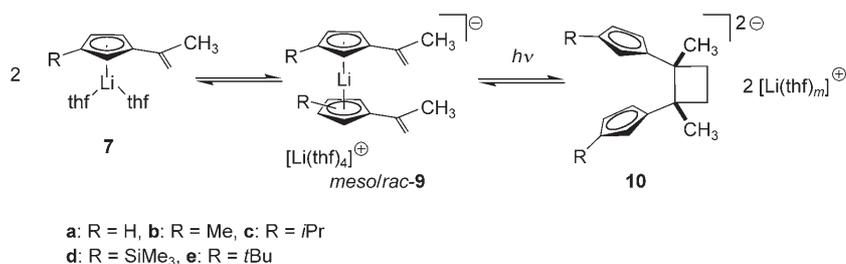


Figure 2. Temperature-dependent ⁷Li NMR spectra (233.1 MHz, [D₈]THF) of the **7e**/*meso*-**9e**/*rac*-**9e** equilibrium.

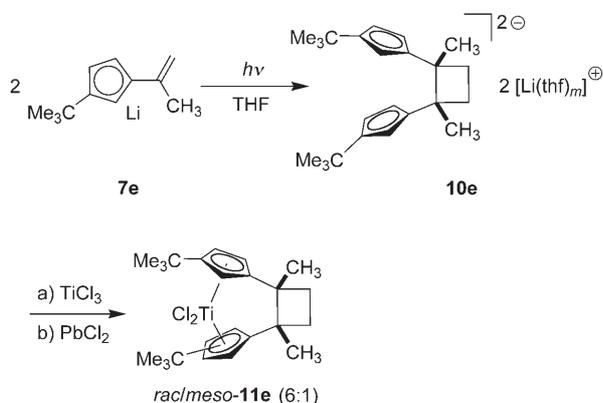
NMR behavior is straightforward: we have most likely monitored the consequences of a rapid equilibration between the THF-stabilized monomer [**7e**(thf)_{*m*}] with the corresponding lithiocene anion **9e** and its [Li(thf)_{*m*}]⁺ ion. The [Li(thf)_{*m*}]⁺ ion equilibrates with the **7e** monomer under our NMR conditions, and the equilibration **7e** ⇌ **9e** + [Li(thf)_{*m*}]⁺ is strongly temperature dependent and shifted almost completely to the right at low temperature (Scheme 4; for further details see the Supporting Information).

We have made use of these characteristic equilibrium features for the photochemical [2+2] cycloaddition at the stage of the functionalized lithiocene. A solution of **7e** in [D₈]THF in a quartz NMR tube was placed in a Schlenk tube (2 cm i.d.) that was filled with acetone. This was placed in a



Scheme 4.

cooling bath (THF) and irradiated at -90°C with a water-cooled HPK 125 lamp (quartz filter) from a distance of 3 cm. Under these specific conditions a slow [2+2] cycloaddition reaction took place that in the course of two days resulted in the clean formation of the cyclized product **10e** (95 % yield along with 5 % starting material; Scheme 5). The obtained



Scheme 5.

mixture seems to represent the photostationary equilibrium under these specific conditions. Further irradiation at -90°C through a THF filter instead of the acetone filter led to a slow conversion to a 70:30 mixture of **7e** and **10e**, similar to the mixture found upon direct irradiation of pure **7e** at -90°C under these conditions with purely THF-filtered light. Photolysis of the reaction mixture after cyclization (95 % **10e**) at room temperature with pyrex-filtered UV light converted it cleanly back to **7e**. Complex **10e** was isolated from several experiments and characterized spectroscopically (see the Experimental Section) and by a transmetalation reaction (see below).

The photochemical [2+2] cycloaddition of the lithiocene is not limited to the example **7e**→**10e** but has been observed with other substituted lithium (alkenyl)cyclopentadienides as well. Thus the low-temperature irradiation of the trimethylsilyl-substituted (methylethenyl)Cp–lithium derivative **7d** (HPK 125, quartz, acetone filter, -90°C) gave 83 % yield of the cyclized product **10d** after 3 days. The isopropyl derivative **7c** cyclized similarly to give 61 % yield of **10c** after 3 days, whereas the methyl-substituted system **7b** was much less efficient in this reaction. The cyclized product **10b** was obtained in a yield of only 39 % of after 4 days of irradiation at -90°C under our typical conditions, and the parent compound (**7a**) did not cyclize at all.

Qualitatively, the observed efficiencies for the [2+2] cycloadditions seem to parallel the **7**⇌**9** equilibrium reached at low temperature. Whereas formation of the lithiocene anion seems to be close to complete at 168 K in the case of the *tert*-butyl derivative **27e**→**9e**, a substantial quantity (ca. 50 %) of the isopropyl-substituted monomer is present under the same conditions in the equilibrium as judged by its prominent ^7Li NMR feature at $\delta = -6.8$ ppm (**9d** lithiocene signal observed at $\delta = -12.2/-12.3$ ppm, $[\text{Li}(\text{thf})_m]^+$ resonance at $\delta = -1.2$ ppm in $[\text{D}_8]\text{THF}$ at 168 K). This trend of

shifting the **27**⇌**9** equilibrium to the monomer side increases steadily with decreasing steric bulk of the substituent R attached to the Cp ring (for details see the Supporting Information).

We have used this method for the preparation of a new ansa titanocene system. The (alkenyl)Cp–lithium reagent **7e** was irradiated under our typical reaction conditions (see above) and the resulting cyclobutylene-linked biscyclopentadienide reagent **10e** was transmetalated by treatment with $[\text{TiCl}_3(\text{thf})_3]$. Subsequent oxidative chlorination by treatment with PbCl_2 ^[13] eventually gave the ansa titanocene complex **11e** in 82 % yield as a 6:1 mixture of the *rac* isomer with one of the two possible *meso* diastereomers (Scheme 5).^[14]

Single crystals were obtained of the minor compound of the mixture, namely *meso*-**11e**. The X-ray crystal structure analysis shows the presence of the cyclobutylene-bridged ansa-metalloocene framework (Figure 3). The C–C σ bonds of the bridging four-membered carbocycle amount to 1.584(5) Å (C10A–C10B) and 1.529(5) Å (C11A–C11B); $d(\text{C10A} - \text{C11A}) = 1.543(5)$ Å, $d(\text{C10B} - \text{C11B}) = 1.550(5)$ Å (for further details see the Supporting Information).

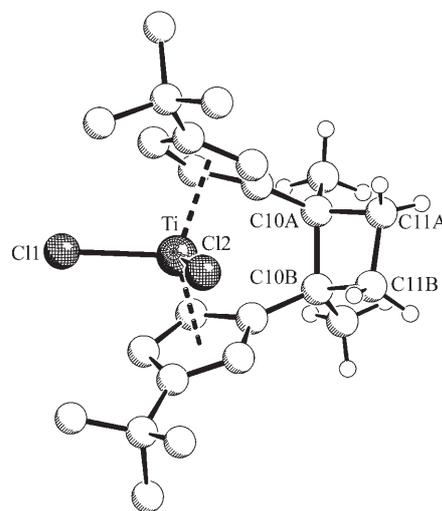


Figure 3. X-ray crystal structure of the *meso*-titanocene dichloride **11e**.

Experimental Section

10e: A Philips HPK lamp (125 W) placed in a water-cooled vacuum-jacketed quartz vessel was used for UV irradiation. A 0.26 M solution of **7e** (prepared by deprotonation of **6e**^[15] with LDA in diethyl ether) in $[\text{D}_8]\text{THF}$ in a 5-mm quartz NMR tube and was placed in a 2-cm i.d. Schlenk tube filled with acetone (10 mL) serving as a filter and for heat transfer. The Schlenk tube was placed at a distance of 3 cm from the light source. The sample was irradiated in a THF-filled cooling bath at -90°C for 2 days. For a preparative reaction **7e** (300 mg, 1.78 mmol) was dissolved in THF (20 mL) (2-cm i.d. Schlenk tube) and photolyzed under similar conditions as described above for 2 days. The solvent was removed in vacuo to give a white solid. The solid was suspended in diethyl ether and the supernatant liquid removed by syringe to separate unreacted starting material. This procedure was repeated twice (2×10 mL diethyl ether). The remaining solid was dried in vacuo to yield 211 mg (71 %) of **10e**. ^1H NMR (599.8 MHz, $[\text{D}_8]\text{THF}$, 75°C): $\delta = 5.23$ (m, 2H), 5.17 (m, 2H), and 5.15 (m, 2H; C_5H_3), 2.49 (m, 2H), and 1.83 (m, 2H; CH_2), 1.47 (s, 6H; CH_3), 1.09 ppm (s, 18H; CH_3); ^{13}C NMR (150.8 MHz, $[\text{D}_8]\text{THF}$,

75 °C): δ = 129.4 (C-q), 127.1 (C-q), 102.9 (CH), 101.3 (CH), 97.6 (CH), 48.3 (C-q), 33.3 (CH₃), 32.1 (C-q), 31.3 (CH₂), 25.9 ppm (CH₃).

11e: A mixture of [TiCl₃(THF)₃] (232 mg) and **10e** (211 mg, 0.63 mmol) was dissolved in 15 mL of precooled THF at -78 °C. The solution was stirred overnight and then warmed to room temperature. The vigorously stirred solution was treated with solid anhydrous lead dichloride (105 mg, 0.38 mmol, 0.6 equiv). The reaction mixture was stirred for an additional 4 h before the solvent was removed in vacuo. The residue was suspended in pentane and the insoluble material removed by filtration through a plug of celite. The solid was washed with pentane until the filtrate was colorless, and the combined filtrates were concentrated in vacuo at -50 °C to give a red precipitate. The supernatant solution was removed by syringe and the solid dried in vacuo. The solution was further concentrated to yield a second fraction of the product (total yield: 227 mg, 82%, *rac/meso-A/meso-B*: 6/1/-); m.p. 202 °C (decomp 319 °C); *meso-11e*: ¹H NMR (599.8 MHz, [D₆]benzene, 25 °C): δ = 6.78 (m, 2H), 6.20 (m, 2H) and 5.90 (m, 2H, C₅H₃), 2.11 (m, 2H) and 1.54 (m, 2H; CH₂), 1.54 (s, 18H; CH₃), 0.99 ppm (s, 6H; CH₃); ¹³C NMR (150.8 MHz, [D₆]benzene, 25 °C): δ = 143.3 (C-q), 140.5 (C-q), 130.6 (CH), 117.1 (CH), 108.0 (CH), 50.4 (C-q), 34.5 (C-q), 31.6 (CH₃), 30.0 (CH₂), 25.8 ppm (CH₃); *rac-11e*: ¹H NMR (599.8 MHz, [D₆]benzene, 25 °C): δ = 6.60 (m, 1H), 6.39 (m, 1H), 6.37 (m, 1H), 6.28 (m, 1H), 6.07 (m, 1H), and 6.02 (m, 1H; C₅H₃), 2.11 (m, 2H), and 1.54 (m, 2H; CH₂), 1.53 (s, 9H) and 1.32 (s, 9H; CH₃), 1.01 ppm (s, 6H; CH₃); ¹³C NMR (150.8 MHz, [D₆]benzene, 25 °C): δ = 155.8 (C-q), 144.4 (C-q), 143.3 (C-q), 140.7 (C-q), 127.9 (CH), 120.2 (CH), 117.1 (CH), 116.2 (CH), 109.7 (CH), 106.7 (CH), 50.5 (C-q), 49.8 (C-q), 34.8 (C-q), 34.6 (C-q), 31.5 (CH₃), 30.4 (CH₃), 29.9 (CH₂), 29.9 (CH₂), 25.6 (CH₃), 25.3 ppm (CH₃); elemental analysis: calcd (%) for C₂₄H₃₄TiCl₂: C 65.32, H 7.77; found: C 64.93, H 7.73. Slow concentration of a solution of *rac/meso-11e* in diethyl ether gave red crystals of *meso-11e* suitable for the X-ray crystal structure analysis.

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- [1] M. Schlosser, *Organometallics in Synthesis*, Wiley, New York, **2001**; B. J. Wakefield, *Organolithium Methods*, Academic Press, London, **1998**; J. Clayden, J. E. Baldwin, *Organolithiums: Selectivity for Synthesis*, Pergamon, New York, **2002**; *Lithium Chemistry, A Theoretical and Experimental Overview* (Eds.: A.-M. Sapse, P. von R. Schleyer), Wiley, New York, **1995**, and references therein.
- [2] For rare exceptions see, for example, H. J. Reich, J. E. Holladay, T. G. Walker, J. L. Thompson, *J. Am. Chem. Soc.* **1999**, *121*, 9769–9780; W. F. Bailey, M. J. Mealy, *J. Am. Chem. Soc.* **2000**, *122*, 6787–6788; X. Wei, R. J. K. Taylor, *Angew. Chem.* **2000**, *112*, 419–422; *Angew. Chem. Int. Ed.* **2000**, *39*, 409–412; D. Cheng, K. R. Knox, T. Cohen, *J. Am. Chem. Soc.* **2000**, *122*, 412–413.
- [3] See, for example, T. Hense, D. Hoppe, *Angew. Chem.* **1997**, *109*, 2377–2410; *Angew. Chem. Int. Ed. Engl.* **1997**, *36*, 2283–2316.
- [4] G. Erker, G. Kehr, R. Fröhlich, *J. Organomet. Chem.* **2004**, *689*, 1402–1412.
- [5] G. Erker, S. Wilker, C. Krüger, R. Goddard, *J. Am. Chem. Soc.* **1992**, *114*, 10983–10984; G. Erker, S. Wilker, C. Krüger, M. Nolte, *Organometallics* **1993**, *12*, 2140–2151; W.-L. Nie, G. Erker, G. Kehr, R. Fröhlich, *Angew. Chem.* **2004**, *116*, 313–317; *Angew. Chem. Int. Ed.* **2004**, *43*, 310–313; N. Iwama, T. Kato, T. Sugano, *Organometallics* **2004**, *23*, 5813–5817.
- [6] P.-J. Sinnema, P. J. Shapiro, B. Höhn, T. E. Bitterwolf, B. Twamley, *Organometallics* **2001**, *20*, 2883–2888.

- [7] For a recent review on organometallic photochemistry see T. E. Bitterwolf, *J. Organomet. Chem.* **2004**, *689*, 3939–3952; see also Q. Chu, D. C. Swenson, L. R. MacGillivray, *Angew. Chem.* **2005**, *117*, 3635–3638; *Angew. Chem. Int. Ed.* **2005**, *44*, 3569–3572, and references therein.
- [8] L. A. Paquette, W. Bauer, M. R. Sivik, M. Bühl, M. Feigel, P. von R. Schleyer, *J. Am. Chem. Soc.* **1990**, *112*, 8776–8789; K. Kunz, J. Pflug, A. Bertuleit, R. Fröhlich, E. Wegelius, G. Erker, E.-U. Würthwein, *Organometallics* **2000**, *19*, 4208–4216; K. Kunz, G. Erker, G. Kehr, R. Fröhlich, *Organometallics* **2001**, *20*, 392–400.
- [9] Reviews: P. Jutzi, *J. Organomet. Chem.* **1990**, *400*, 1–17; P. Jutzi, *Pure Appl. Chem.* **1990**, *62*, 1035–1038; P. Jutzi, *Pure Appl. Chem.* **1989**, *61*, 1731–1736; P. Jutzi, *Adv. Organomet. Chem.* **1986**, *26*, 217–295; E. Weiss, *Angew. Chem.* **1993**, *105*, 1565–1587; *Angew. Chem. Int. Ed. Engl.* **1993**, *32*, 1501–1523; D. Stahlke, *Angew. Chem.* **1994**, *106*, 2256–2259; *Angew. Chem. Int. Ed. Engl.* **1994**, *33*, 2168–2171; P. Jutzi, N. Burford, *Chem. Rev.* **1999**, *99*, 969–990; P. Jutzi, G. Reumann, *Dalton Trans.* **2000**, 2237–2244; P. H. M. Budzelaar, J. J. Engelberts, J. H. van Lenthe, *Organometallics* **2003**, *22*, 1562–1576.
- [10] K. Ziegler, W. Schäfer, *Justus Liebigs Ann. Chem.* **1934**, *511*, 101–109; K. Ziegler, H.-G. Gellert, H. Martin, K. Nagel, J. Schneider, *Justus Liebigs Ann. Chem.* **1954**, *589*, 91–121; M. F. Sullivan, W. F. Little, *J. Organomet. Chem.* **1967**, *8*, 277–285; P. Renaut, G. Tainturier, B. Gautheron, *J. Organomet. Chem.* **1978**, *148*, 43–51; J. Okuda, *Chem. Ber.* **1989**, *122*, 1075–1077; G. Erker, R. Nolte, Y.-H. Tsay, C. Krüger, *Angew. Chem.* **1989**, *101*, 642–644; *Angew. Chem. Int. Ed. Engl.* **1989**, *28*, 628–629; G. Erker, R. Nolte, R. Aul, S. Wilker, C. Krüger, R. Noe, *J. Am. Chem. Soc.* **1991**, *113*, 7594–7602; R. R. Squires, *Acc. Chem. Res.* **1992**, *25*, 461–467.
- [11] K. J. Stone, R. D. Little, *J. Org. Chem.* **1984**, *49*, 1849–1853.
- [12] See for a comparison: A. Hammel, W. Schwarz, J. Weidlein, *Acta Crystallogr. Sect. C* **1990**, *46*, 2337–2339.
- [13] G. A. Luinstra, J. H. Teuben, *J. Chem. Soc. Chem. Commun.* **1990**, 1470–1471.
- [14] This synthesis is especially useful since we could not prepare complex **11e** in analogy to the zirconium analogue^[5] by photochemical [2+2] cycloaddition of the corresponding (alkenylCp)₂TiCl₂ system.
- [15] T. J. Clark, T. A. Nile, *Synlett* **1990**, 589–590.