

# Studies on the Thermolysis of Ether-Stabilized $\text{Lu}(\text{CH}_2\text{SiMe}_3)_3$ . Molecular Structure of $\text{Lu}(\text{CH}_2\text{SiMe}_3)_3(\text{THF})(\text{diglyme})$

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$\text{Lu}(\text{CH}_2\text{SiMe}_3)_3(\text{THF})_2$  (**2**) decomposes slowly at room temperature with formation of  $\text{Me}_4\text{Si}$ . In order to understand the mechanism of this elimination process,  $\text{Lu}(\text{CH}_2\text{SiMe}_3)_3([\text{D}_8]-\text{THF})_2$  (**1**),  $\text{Lu}(\text{CH}_2\text{SiMe}_3)_3(\text{THF})(\text{DME})$  (**3**), and  $\text{Lu}(\text{CH}_2\text{SiMe}_3)_3(\text{THF})(\text{diglyme})$  (**4**) were prepared. The results of  $^1\text{H}$  NMR spectroscopic studies of the decomposition in solution exclude an  $\alpha$ - as well as a  $\beta$ -H elimination mechanism and point towards a  $\gamma$ -H elimination. The molecular structure of **4** has been determined by single crystal X-ray diffraction.

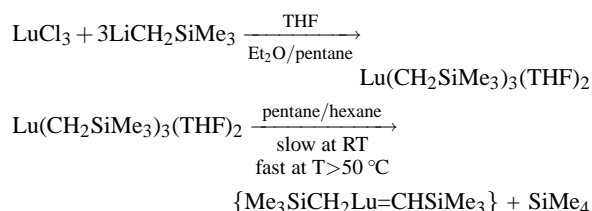
**Key words:** Lutetium Alkyls, Decomposition, X-Ray Structure,  $\gamma$ -H Elimination

## Introduction

Until recently chemical bonding in coordination and organometallic compounds of the lanthanides has been considered as purely ionic with the metal  $d$  orbitals not involved in covalent  $\sigma$ - or  $\pi$ -bonds [1]. However, some experimental observations cannot be understood on this simple basis. Very recently the first examples of imido complexes of the lanthanides have been described [2–4], in which the  $5d$  metal acceptor orbitals appear to play a significant role in stabilizing  $\pi$ -donation from imido groups to a lanthanide (Sm) center [5].

Related lanthanide alkylidene complexes are less well known. In examples containing either neutral simple imidazol-2-ylidene [5–7] or bis(iminodiphenylphosphorano)methylidene ligands [7], the carbenoid carbon atoms are stabilized by directly bound heteroatoms, and the Ln–C bonds cannot be considered to have true metallaalkene character.

In 1978 we synthesized THF adducts of homoleptic alkyl complexes  $\text{Ln}(\text{CH}_2\text{SiMe}_3)_3$  of the late lanthanides Er, Tm, and Lu (Scheme 1) [8–10] and studied their thermal decomposition. We found that these complexes are rather unstable and decompose evolving  $\text{Me}_4\text{Si}$  to leave THF-free polymeric materials. These products are insoluble in organic solvents, but upon quenching with  $\text{D}_3\text{O}^+$  gave rise to singly as



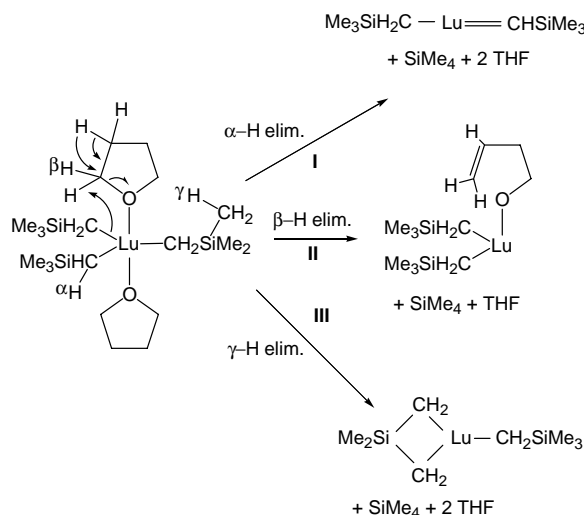
Scheme 1.

well as doubly deuterated  $\text{Me}_4\text{Si}$ . This fact was interpreted by assuming formation of lanthanide alkylidene complexes resulting from  $\alpha$ -H-elimination of one of the  $\text{Me}_3\text{SiCH}_2$  groups (Scheme 1) [9]. However, this mechanism was not sufficiently proven and the nature of the decomposition products was not studied any further.

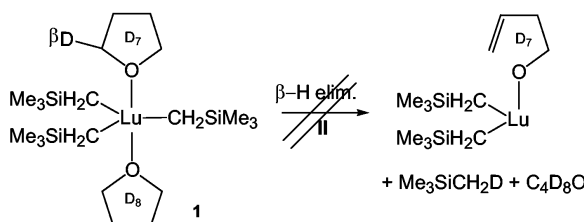
In order to support the proposed formation of  $\text{Ln}=\text{C}$  species, we decided to reinvestigate the thermal decomposition of  $\text{Lu}(\text{CH}_2\text{SiMe}_3)_3(\text{THF})_2$  with the aim to delineate the elimination pathway in this particular case. In addition, we synthesized other ether adducts of  $\text{Lu}(\text{CH}_2\text{SiMe}_3)_3$  and studied their chemical and thermal stability.

## Results and Discussion

Three elimination pathways can be proposed for the thermal decomposition of  $\text{Lu}(\text{CH}_2\text{SiMe}_3)_3(\text{THF})_2$



Scheme 2.



Scheme 3.

forming  $\text{SiMe}_4$ : i) *via*  $\alpha$ -H elimination from a  $\text{Lu}-\text{SiCH}_3$  group (I), ii) *via*  $\beta$ -H elimination from a THF ligand (II), and iii) *via*  $\gamma$ -H elimination releasing a hydrogen from a  $\text{SiCH}_3$  group (III) (Scheme 2).

It is well known that the CH-acidity of O-CH<sub>2</sub>-protons in coordinated THF is higher than in free THF, therefore decomposition of  $\text{Lu}(\text{CH}_2\text{SiMe}_3)_3(\text{THF})_2$  can in principle proceed *via* activation of such a proton. In order to study this possibility we synthesized  $\text{Lu}(\text{CH}_2\text{SiMe}_3)_3([\text{D}_8]\text{-THF})_2$  (1) and thermolyzed it in hexane at elevated temperatures (Scheme 3). No formation of  $\text{Me}_3\text{SiCH}_2\text{D}$  was observed by NMR and GC-MS analysis of the products in solution. Based on these results a  $\beta$ -H-elimination mechanism can be ruled out.

Decomposition of  $\text{Lu}(\text{CH}_2\text{SiMe}_3)_3(\text{THF})_2$  (2) either *via*  $\alpha$ -H- or  $\gamma$ -H-elimination should yield  $\text{Me}_4\text{Si}$  and organolutetium compounds. After  $\text{D}_3\text{O}^+$  quenching these residues are expected to form  $\text{Me}_3\text{SiCH}_2\text{D}$  and  $\text{Me}_3\text{SiCHD}_2$  as deuterolysis products of  $\text{Me}_3\text{SiCH}_2\text{Lu}=\text{CHSiMe}_3$  in the case of  $\alpha$ -H elimination, and  $\text{Me}_3\text{SiCH}_2\text{D}$  and  $\text{Me}_2\text{Si}(\text{CH}_2\text{D})_2$  gener-

ated by deuterolysis of  $\text{Me}_3\text{SiCH}_2\text{Lu}(\mu\text{-CH}_2)_2\text{SiMe}_3$  in the case of  $\gamma$ -H elimination. Heating of 2 in hexane to 60 °C for 4 days gave an extremely air-sensitive yellowish product which turns white immediately when exposed to air. Hydrolysis of this product with  $\text{D}_3\text{PO}_4$  in  $[\text{D}_6]$ -benzene did not result in the formation of any  $\text{Me}_3\text{SiCHD}_2$ . In the  $^{13}\text{C}\{^1\text{H}\}$  NMR spectrum the 1 : 1 : 1 : 1 : 1 quintet of  $\text{Me}_3\text{SiCHD}_2$  was not observed but two 1 : 1 : 1 triplets appeared with  $^1J_{\text{C-D}}$  coupling constants of 18 Hz which can be assigned to the deuterolysis product  $\text{Me}_2\text{Si}(\text{CH}_2\text{D})_2$ , proving the fact that  $\gamma$ -H elimination of  $\text{Me}_4\text{Si}$  is the predominant decomposition pathway of 2.

X-ray structural investigations of  $\text{Lu}(\text{CH}_2\text{SiMe}_3)_3(\text{THF})_2$  (2) proved the molecule to have a trigonal bipyramidal structure with the  $\text{Me}_3\text{SiCH}_2$  ligands in equatorial and the THF ligands in apical positions. The angle O-Lu-O of 177.73° indicates only a minor deviation from the ideal linear arrangement. On the other hand, the three  $\text{Me}_3\text{SiCH}_2$  ligands are distributed unsymmetrically with C-Lu-C angles of 110.00, 116.16, and 133.74°. Two  $\text{Me}_3\text{Si}$  groups face each other, impeding any  $\alpha$ -elimination of  $\text{Me}_4\text{Si}$  (Fig. 1) [11].

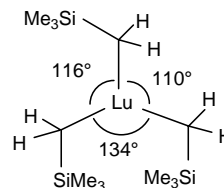
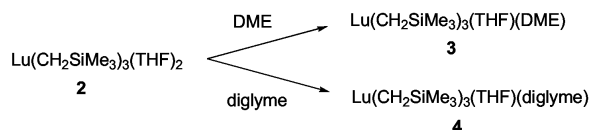


Fig. 1. View along the O-Lu-O axis to the  $\text{LuC}_3$  plane in  $\text{Lu}(\text{CH}_2\text{SiMe}_3)_3(\text{THF})_2$  (2).

In order to facilitate  $\alpha$ -H elimination as a decomposition pathway we decided to preorganize the *cis*-configuration of the alkyl groups in the coordination sphere of the Lu center by synthesizing other ether adducts of  $\text{Lu}(\text{CH}_2\text{SiMe}_3)_3$  using chelating ligands like DME and diglyme. However, alkylation of  $\text{LuCl}_3$  with  $\text{LiCH}_2\text{SiMe}_3$  in DME/pentane under reaction conditions used for the synthesis of 2 did not yield DME-solvated  $\text{Lu}(\text{CH}_2\text{SiMe}_3)_3$ , but gave only viscous insoluble materials. Probably “ate”-complexes analogous to  $[\text{Li}(\text{TMEDA})_2]^+[\text{Lu}(\text{CH}_2\text{SiMe}_3)_4]^-$  are formed in these reactions as in the presence of TMEDA [9, 10].

Substitution of THF ligands in 2 by DME resulted in an increase of the coordination number of Lu to six and formation of the lutetium complex 3 bearing one THF and one chelating DME ligand (Scheme 4),



Scheme 4.

as demonstrated by the  $^1\text{H}$  and  $^{13}\text{C}$  NMR spectra of the product **3**. Unfortunately its crystal structure could not be refined satisfactorily because of disorder of the coordinated THF and DME molecules [12]. It appears that in contrast to the direct synthesis of  $\text{Lu}(\text{CH}_2\text{SiMe}_3)_3(12\text{-crown-4})$  from **2** and 12-crown-4, recently described [13], substitution of only one THF by DME has occurred. A further displacement of coordinated THF by DME could not be accomplished.

The reaction of **2** with diglyme proceeds similarly (Scheme 4), yielding the octahedrally coordinated mixed THF/diglyme lutetium complex **4**. The product crystallizes from pentane at  $-10^\circ\text{C}$  as colorless needles. The diglyme ligand is coordinated to lutetium only *via* two oxygen atoms leaving a dangling  $\text{CH}_2\text{CH}_2\text{OMe}$  arm (Fig. 2).

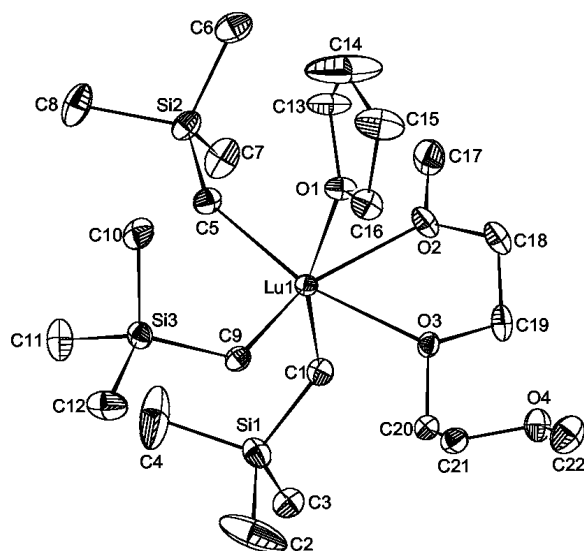


Fig. 2. ORTEP [14] drawing and numbering scheme of the molecular structure of **4** (30% probability thermal ellipsoids); all hydrogen atoms have been omitted for clarity; selected bond lengths (Å) and angles ( $^\circ$ ): Lu-C(1) 2.375(6), Lu-C(5) 2.347(6), Lu-C(9) 2.375(6), Lu-O(1) 2.432(4), Lu-O(2) 2.407(4), Lu-O(3) 2.450(4), C(1)-Lu-C(5) 98.7(2), C(1)-Lu-C(9) 106.2(2), C(1)-Lu-O(2) 85.44(18), C(1)-Lu-O(3) 87.07(18), C(5)-Lu-C(9) 103.1(2), C(5)-Lu-O(1) 91.47(19), C(5)-Lu-O(2) 101.45(19), C(9)-Lu-O(1) 88.23(18), C(9)-Lu-O(3) 86.70(17), O(1)-Lu-O(2) 75.43(15), O(1)-Lu-O(3) 79.54(14), O(2)-Lu-O(3) 66.75(13).

The molecular structure of **4** shows the lutetium atom in a distorted *fac*-octahedral coordination very similar to that found in  $\text{Sm}(\text{CH}_2\text{SiMe}_3)_3(\text{THF})_3$  [11]. Most angles at the lutetium atom deviate strongly from linearity or from  $90^\circ$ . The smallest angle O(2)-Lu-O(3) ( $66.75^\circ$ ) is a result of the geometry of the diglyme molecule. The steric demand of the  $\text{Me}_3\text{Si}$  groups bonded to C(5) and C(9) causes a widening of the angles C(5)-Lu-C(9) ( $103.1^\circ$ ) and C(5)-Lu-O(2) ( $101.45^\circ$ ), but nevertheless an almost planar coordination of C(5), C(9), O(3) and O(2) around the lutetium atom results, including a small C(9)-Lu-O(3) angle of  $86.70^\circ$ . Owing to the small difference in the atomic radii of samarium and lutetium [15], the Ln-C bond lengths are generally the same in **4** and  $\text{Sm}(\text{CH}_2\text{SiMe}_3)_3(\text{THF})_3$  [11]. They are also equal in the distorted trigonal bipyramidal complex **2** and in the *fac*-octahedral molecule **4**.

In contrast to **2**, the two mixed adducts **3** and **4** are thermally robust complexes. **4** shows only little decomposition after heating for 2 days in heptane to  $70\text{--}90^\circ\text{C}$ . This observation undoubtedly confirms that  $\alpha\text{-H}$  elimination is clearly not a favourable process in the thermal decomposition of  $\text{Ln}(\text{CH}_2\text{SiMe}_3)_3$  ether adducts. The remaining  $\gamma\text{-H}$  elimination pathway, yielding  $\text{Me}_4\text{Si}$  and  $\text{Me}_3\text{SiCH}_2\text{Lu}(\mu\text{-CH}_2)_2\text{SiMe}_2$ , has to be confirmed or excluded by further investigations.

## Experimental Section

All experiments were performed in an atmosphere of dry, oxygen-free nitrogen using Schlenk techniques and solvents dried over sodium/benzophenone and distilled prior to use.  $\text{LuCl}_3$  [16] and  $\text{LiCH}_2\text{SiMe}_3$  [17] as well as  $\text{Lu}(\text{CH}_2\text{SiMe}_3)_3([\text{D}_8]\text{-THF})_2$  (**1**) and  $\text{Lu}(\text{CH}_2\text{SiMe}_3)_3(\text{THF})_2$  (**2**) [8] were synthesized according to literature methods. NMR spectra were recorded using Bruker ARX 200 and 400 spectrometers. Lu was determined complexometrically against xylenolorange after digestion in 60%  $\text{HClO}_4$  at pH 6 to 7 [18].

### $\text{Lu}(\text{CH}_2\text{SiMe}_3)_3([\text{D}_8]\text{-THF})_2$ (**1**) [8]

$^1\text{H}$  NMR ( $[\text{D}_6]$ -benzene, 200 MHz):  $\delta = 0.18$  (s, 27 H,  $\text{CH}_3\text{Si}$ ),  $-1.02$  (s, 6 H,  $\text{CH}_2$ ).  $^{13}\text{C}\{^1\text{H}\}$  NMR ( $[\text{D}_6]$ -benzene, 50 MHz):  $\delta = 4.5$  ( $\text{CH}_3\text{Si}$ ),  $24.7$  ( $\text{CH}_2$ ).

### $\text{Lu}(\text{CH}_2\text{SiMe}_3)_3(\text{THF})_2$ (**2**) [8]

$^1\text{H}$  NMR ( $[\text{D}_6]$ -benzene, 200 MHz):  $\delta = -0.99$  (s, 6 H,  $\text{LuCH}_2$ ),  $0.19$  (s, 27 H,  $\text{CH}_3\text{Si}$ ),  $1.35$  (m, 8 H, THF),  $3.94$

(m, 8 H, THF). –  $^{13}\text{C}\{^1\text{H}\}$  NMR ( $[\text{D}_6]$ -benzene, 50 MHz):  $\delta = 4.7$  ( $\text{CH}_3\text{Si}$ ), 25.1 ( $\text{LuCH}_2$ ), 41.7 (THF), 71.0 (THF).

#### $\text{Lu}(\text{CH}_2\text{SiMe}_3)_3(\text{THF})(\text{DME})$ (**3**)

To a solution of **2** (290 mg, 0.5 mmol) in pentane (10 ml) a mixture of DME (1 ml, 10 mmol) and pentane (10 ml) was added *via* syringe. The reaction mixture was slowly cooled first to 0 °C and then to –30 °C. A white crystalline material precipitated. The reaction vessel was cooled to –78 °C and the mother solution was decanted under nitrogen. The residue was dried under vacuum yielding 300 mg (100%) of colorless crystals of **3**. –  $^1\text{H}$  NMR ( $[\text{D}_6]$ -benzene, 400 MHz):  $\delta = -0.68$  (s, 6 H,  $\text{LuCH}_2$ ), 0.35 (s, 27 H,  $\text{SiCH}_3$ ), 1.33 [m, 4 H,  $\beta\text{-CH}_2(\text{THF})$ ], 2.73 [ $\text{s}_{\text{br}}$ , 4 H,  $\text{OCH}_2(\text{DME})$ ], 3.08 [ $\text{s}_{\text{br}}$ , 6 H,  $\text{OCH}_3(\text{DME})$ ], 3.63 [ $\text{s}_{\text{br}}$ , 4 H,  $\alpha\text{-CH}_2(\text{THF})$ ]. –  $^{13}\text{C}\{^1\text{H}\}$  NMR ( $[\text{D}_6]$ -benzene, 100.64 MHz):  $\delta = 4.7$  ( $\text{CH}_3\text{Si}$ ), 25.2 ( $\text{LuCH}_2$ ), 42.3 [ $\beta\text{-CH}_2(\text{THF})$ ], 61.0 [ $\text{CH}_2(\text{DME})$ ], 69.5 [ $\alpha\text{-CH}_2(\text{THF})$ ], 70.8 [ $\text{CH}_3(\text{DME})$ ]. –  $\text{C}_{20}\text{H}_{51}\text{LuO}_3\text{Si}_3$  (598.85): calcd. C 40.11, H 8.58, Lu 29.22; found C 40.58, H 8.09, Lu 29.43.

#### $\text{Lu}(\text{CH}_2\text{SiMe}_3)_3(\text{THF})(\text{diglyme})$ (**4**)

**4** was synthesized analogously to **3** from **2** (520 mg, 0.9 mmol) and diglyme (1 ml) in hexane (50 ml). Yield 575 mg (> 99%) of colorless crystals. –  $^1\text{H}$  NMR ( $[\text{D}_6]$ -benzene, 400 MHz):  $\delta = -0.70$  (s, 6 H,  $\text{LuCH}_2$ ), 0.40 (s, 27 H, ( $\text{SiCH}_3$ ), 1.41 [m, 4 H,  $\beta\text{-CH}_2(\text{THF})$ ], 2.76 [ $\text{s}_{\text{br}}$ , 4 H,  $\text{OCH}_2(\text{diglyme})$ ], 3.11 [ $\text{s}_{\text{br}}$ , 10 H,  $\text{CH}_3\text{OCH}_2(\text{diglyme})$ ], 3.61 [m, 4 H,  $\alpha\text{-CH}_2(\text{THF})$ ]. –  $^{13}\text{C}\{^1\text{H}\}$  NMR ( $[\text{D}_6]$ -benzene, 100.64 MHz):  $\delta = 4.8$  ( $\text{SiCH}_3$ ), 25.6 ( $\text{LuCH}_2$ ), 41.0 [ $\beta\text{-CH}_2(\text{THF})$ ], 60.6 [ $\text{CH}_2(\text{diglyme})$ ], 68.6 [ $\alpha\text{-CH}_2(\text{THF})$ ], 69.6 [ $\text{CH}_3(\text{diglyme})$ ]. –  $\text{C}_{22}\text{H}_{55}\text{LuO}_4\text{Si}_3$  (642.90): calcd. C 41.10, H 8.62, Lu 27.22; found C 40.51, H 8.29, Lu 27.78.

#### Thermal decompositions of **1**

Freshly recrystallized **1** (300 mg) was put in a 25 ml Schlenk vessel, dissolved in hexane (10 ml), exposed to a slight vacuum and allowed to stand in an oil bath at 60 °C for 4 d. Already after one night a yellow precipitate was formed, leaving the solution colorless and transparent. GC-MS analysis of the hexane solution showed different hexanes, a small amount of pentane,  $\text{Me}_4\text{Si}$  and  $[\text{D}_8]\text{-THF}$ .  $\text{Me}_3\text{SiCH}_2\text{D}$  could not be detected.

#### Thermal decomposition of **2**

Freshly recrystallized **2** (500 mg) was put in a 50 ml Schlenk vessel, dissolved in hexane (25 ml), exposed to a

slight vacuum and allowed to stand in an oil bath at 60 °C for 4 d. The yellowish precipitate was filtered, washed two times with hexane and dried *in vacuo* at 80 °C. Then  $[\text{D}_6]$ -benzene (5 ml) was added and a solution of  $\text{P}_4\text{O}_{10}$  (1 g) in  $\text{D}_2\text{O}$  (10 ml) was added dropwise *via* a septum. After completion of the exothermic reaction, the mixture was cooled to 10 °C and the upper  $[\text{D}_6]$ -benzene layer was slowly syringed to a Schlenk flask containing  $\text{Na}_2\text{SO}_4$  (1 g) and equipped with a presealed NMR-tube. After standing for 1 h, the solution was slowly decanted into the NMR tube, which was immediately sealed off. –  $^{13}\text{C}\{^1\text{H}\}$  NMR ( $[\text{D}_6]$ -benzene, 50 MHz):  $\delta = -0.45$  (t,  $^1J_{\text{CD}} = 18$  Hz,  $\text{CH}_2\text{D}$ ),  $-0.43$  (t,  $^1J_{\text{CD}} = 18$  Hz,  $\text{CH}_2\text{D}$ ),  $-0.16$  (s,  $\text{CH}_3$ ),  $-0.12$  (s,  $\text{CH}_3$ ).

#### Crystallography

Data were collected on a Siemens SMART CCD diffractometer (graphite monochromated Mo- $K_\alpha$  radiation,  $\lambda = 0.71073$  Å) with area-detector by use of  $\omega$  scans at 173 K. The structure was solved by direct methods and refined on  $F^2$  using all reflections with SHELX-97 [19]. All non-hydrogen atoms were refined anisotropically. The hydrogen atoms were placed in calculated positions and assigned to an isotropic displacement parameter of  $0.08$  Å<sup>2</sup>. The idealised methyl-groups were allowed to rotate about their X-C bond. SADABS [20] was used to perform area-detector scaling and absorption corrections.

#### Crystal data and structure refinement details:

$\text{C}_{22}\text{H}_{55}\text{LuO}_4\text{Si}_3$ ,  $M = 642.90$ , monoclinic,  $a = 19.8966(3)$ ,  $b = 18.3186(3)$ ,  $c = 19.4804(2)$  Å,  $\beta = 112.748^\circ$ ,  $V = 6547.88$  Å<sup>3</sup>, space group  $C2/c$  (no. 15),  $Z = 8$ ,  $\mu = 3.146$  mm<sup>–1</sup>,  $D_{\text{calcd.}} = 1.304$  g cm<sup>–3</sup>,  $\theta$  range  $1.57$ – $25.00$  deg; 19996 reflections measured, 5762 unique ( $R_{\text{int}} = 0.0773$ ).  $GOF$  on  $F^2$  1.041. The final residuals  $R_F(wR_F^2)$  were  $0.0419$  ( $0.0746$ ) [ $I > 2\sigma(I)$ ].

Crystallographic data for the structure of **4** have been deposited with the Cambridge Crystallographic Data Centre, CCDC-245414. Copies of the data can be obtained free of charge on application to The Director, CCDC, 12 Union Road, Cambridge CB2 1EZ, UK (Fax: int.code+(1223)336-033; e-mail for inquiry: fileserv@ccdc.cam.ac.uk).

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- [1] R. Anwender, in S. Kobayashi (ed.): Lanthanides: Chemistry and Use in Organic Synthesis, Springer, Berlin (1999).
- [2] H. S. Chan, H. W. Li, Z. Xie, Chem. Commun. 652 (2002).
- [3] J. C. Gordon, G. R. Giesbrecht, D. L. Clark, P. J. Hay, D. W. Keogh, R. Poli, B. L. Scott, J. G. Watkin, Organometallics **21**, 4726 (2002).
- [4] E. D. Brady, D. L. Clark, J. C. Gordon, P. J. Hay, D. W. Keogh, R. Poli, B. L. Scott, J. G. Watkin, Inorg. Chem. **42**, 6682 (2003).
- [5] H. Schumann, M. Glanz, J. Winterfeld, H. Hemling, N. Kuhn, T. Kratz, Angew. Chem. **106**, 1829 (1994); Angew. Chem. Int. Ed. Engl. **33**, 1733 (1994).
- [6] A. J. Arduengo III, M. Tamm, S. J. McLain, J. C. Calabrese, F. Davidson, W. J. Marshall, J. Am. Chem. Soc. **116**, 7927 (1994).
- [7] K. Aparna, M. Ferguson, R. G. Cavell, J. Am. Chem. Soc. **122**, 726 (2000).
- [8] H. Schumann, J. Müller, J. Organomet. Chem. **146**, C5 (1978).
- [9] J. Müller, Dissertation Technische Universität Berlin (1978).
- [10] H. Schumann, J. Müller, J. Organomet. Chem. **169**, C1 (1979).
- [11] H. Schumann, D. M. M. Freckmann, S. Dechert, Z. Anorg. Allg. Chem. **628**, 2422 (2002).
- [12] D. M. M. Freckmann, Dissertation Technische Universität Berlin (2003).
- [13] S. Arndt, P. M. Zeimentz, T. P. Spaniol, J. Okuda, M. Honda, K. Tatsumi, Dalton Trans. 3622 (2003).
- [14] L. Zsolnai, H. Pritzkow, ZORTEP, ORTEP Program for PC, Universität Heidelberg (1994).
- [15] R. D. Shannon, Acta Crystallogr. **A32**, 751 (1976).
- [16] G. Brauer, Handbuch der präparativen Anorganischen Chemie, F. Enke Verlag, Stuttgart (1962).
- [17] H. L. Lewis, T. L. Brown, J. Am. Chem. Soc. **92**, 92, (1979).
- [18] M. Glanz, S. Dechert, H. Schumann, D. Wolff, J. Springer, Z. Anorg. Allg. Chem. **626**, 2467 (2000).
- [19] G. M. Sheldrick, SHELX-97, Program for Crystal Structure Determination, Universität Göttingen (1997).
- [20] G. M. Sheldrick, SADABS Program for Empirical Absorption Correction of Area Data; Universität Göttingen (1996).