



A neutral low-coordinate heterocyclic bismuth-tin species†

C. Hering-Junghans,^a A. Schulz^{*ab} and A. Villingner[†]

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The reaction of distannadiazane bearing bulky ^RAr*-groups (^RAr* = C₆H₂{C(H)Ph₂}₂R-2,6,4; R = *i*Pr, *t*Bu) with ECl₃ (E = Sb, Bi) was studied resulting in the isolation of previously unknown *N,N*-bis-(dichloropnictino)amines (**3**) and a novel heterocyclic carbenoid bismuth species (**4**) bearing a Bi^(III) and a Sn^(IV) center. The structure and bonding was investigated by means of X-ray structure elucidations and DFT calculations.

Pnictogen–nitrogen heterocycles of the type [XE(μ-NR)]₂ (E = P, As, Sb, Bi; species I in Fig. 1) are valuable starting materials for preparative E–N chemistry.¹ Usually, [CIE(μ-NR)]₂ (E = P, As) is prepared from RN(ECl₂)H in a base-assisted (*e.g.* NEt₃) cyclization,² however, for the heavier analogs this strategy works poorly. For example, [ClBi(μ-NTer)]₂ (Ter = terphenyl = 2,6-bis-(2,4,6-trimethylphenyl)phenyl) was initially obtained in moderate yields of 45% besides large amounts of ClBi(N(H)Ter)₂.³ In analogy to Veith's synthesis of [Me₂SiE(μ-N*t*Bu)]⁺ (II in Fig. 1),⁴ our group succeeded in establishing a straightforward route towards the synthesis of [CIE(μ-NTer)]₂ (E = Sb, Bi), based on the *trans*-metalation of the respective tin precursor.⁵ Now highly reactive *cyclo*-1,3-dipnicta-2,4-diazanium salts of the type [E(CIE)(μ-NTer)]⁺ (E = P, As,⁶ Sb, Bi;⁵ III in Fig. 1) can be obtained by chloride abstraction from [CIE(μ-NTer)]₂ by means of Lewis acids such as GaCl₃. A new area of research opened up with the isolation of thermally stable biradicaloids of the type [E(μ-NTer)]₂ (E = P, As; IV in Fig. 1) which can easily be accessed by reduction of [CIE(μ-NTer)]₂ with activated magnesium chips.⁷

Just recently, we described the synthesis of stable acyclic chloropnictenium ion salts, with an exceedingly bulky ^RAr*-group (Ar* = C₆H₂{C(H)Ph₂}₂R-2,6,4; R = Me, *t*Bu) attached to the nitrogen atom.⁸

This sterically demanding moiety offers two flanking phenyl groups for arene-interactions with the low-coordinate reactive site of the molecules. Jones and co-workers realized new bonding situations with the aid of the ^RAr*-moiety,⁹ such as mono-coordinate Ge or Sn cations,¹⁰ singly bonded distannyne and Ge and Sn hydride complexes,^{11,12} that showed magnificent activity as a catalyst in hydroboration reactions.¹³ Just recently, the first example of an amido-distibene in [Pr^{Ar*}N(SiPr₃)Sb]₂ was reported.¹⁴ Herein we describe the synthesis of an unprecedented distannadiazane [Sn(μ-N^RAr*)]₂ with a planar N₂Sn₂-core and its *trans*-metalation with ECl₃ (E = Sb, Bi), resulting in the isolation of the first *N,N*-bis(dichlorostibino)amine and an elusive four-membered ring system with a N₂Bi^(III)Sn^(IV) unit.

In analogy to a procedure described by Power *et al.*, leading to the first isolable distannadiazane [Sn(μ-NTer)]₂,¹⁵ the exceedingly bulky amine ^tBuAr*NH₂ and Sn{N(SiMe₃)₂}₂ were combined in a Schlenk flask without solvent and heated to 160 °C over a period of 45 min, affording a deep red solid. HN(SiMe₃)₂ and excess Sn{N(SiMe₃)₂}₂ were removed *in vacuo* and the crude product was recrystallized from C₆H₅F to obtain red crystals of [Sn(μ-N^tBuAr*)]₂ (**1R**, R = *t*Bu) in moderate yields (64%). The synthesis of **1Me** and **1iPr** suffered from low solubility of the products in common organic solvents, however, minimal amounts of X-ray quality crystals of **1iPr** were obtained from C₆H₆. In the ¹³C and ¹H NMR spectrum **1iPr** and **1tBu** can be easily identified by the signals of the *para*-substituent of the inner phenyl group and their diagnostic ¹¹⁹Sn NMR shifts

^a Institut für Chemie, Universität Rostock, Albert-Einstein-Str. 3a, 18059 Rostock, Germany. E-mail: axel.schulz@uni-rostock.de

^b Abteilung Materialdesign, Leibniz-Institut für Katalyse e.V. an der Universität Rostock, Albert-Einstein-Str. 29a, 18059 Rostock, Germany

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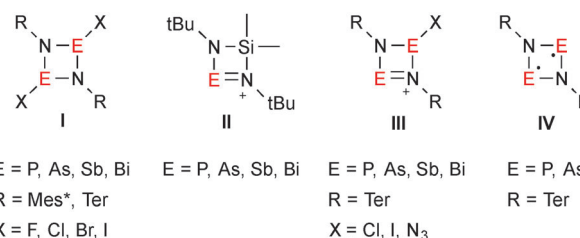


Fig. 1 Selected known four-membered E–N heterocycles.^{4–7}



(**1iPr** 783.1 ppm, **1tBu** 789.2 ppm; *cf.* [Sn(μ -Nter)]₂ 738.9 ppm). **1iPr** and **1tBu** crystallize as solvates of C₆H₆ or C₆H₅F (see Fig. S1 and S4 in the ESI[†]), respectively, in the triclinic space group *P* $\bar{1}$ with one molecule in the asymmetric unit, which lies on a crystallographically imposed centre of inversion. In contrast to [Sn(μ -Nter)]₂, in which the Sn₂N₂ ring is characterized by a folding about the Sn...Sn axis of 148°, the Sn₂N₂-core is planar with slightly different N1–Sn1 and N1'–Sn1' distances (**1iPr** 2.076(2), 2.086(2); **1tBu** 2.075(2), 2.090(2) Å; *cf.* [Sn(μ -Nter)]₂ 2.09, 2.11 Å), a transannular Sn1...Sn1' separation of 3.2304(4) (**1iPr**) and 3.2318(3) Å (**1tBu**) and rather acute angles at the tin center (**1iPr** 78.27(7), **1tBu** 78.22(6)°, *cf.* [Sn(μ -Nter)]₂ 77.6°).¹⁵ The nitrogen atoms are in a planar environment as expected for a formal sp²-hybridized center with a p-type lone pair (LP) of electrons. Hence, the planarity of the core is imposed by the increasing bulkiness of the *t*BuAr*–moieties, as a bend core would result in pyramidalization about the N atoms to fit both RAr*–groups in. Just recently, the bonding in [E(μ -Nter)]₂ (E = Ge, Sn, Pb) was studied in detail by Ziegler *et al.*, who analysed the interaction of the monomeric units E(μ -Nter) in the dimeric structure, with the result that the dimer is kept together by two σ - and π -bonds.¹⁶

Combining red **1tBu** with two equivalents of SbCl₃ in CH₂Cl₂ resulted in an immediate decolourisation, accompanied by a colourless precipitate (Scheme 1, reaction (ii)), which was removed by filtration and from the filtrate X-ray quality crystals of *trans*-[ClSb(μ -Nter)]₂ (**2**) were grown overnight at room temperature. This metathesis route gives **2** reproducibly in good yields, while using the elimination of SnCl₂ as the driving force, which dates back to the seminal work of Veith,¹⁷ who established this route to prepare [Me₂SiECl(μ -N*t*Bu)]₂ ring systems (*vide supra*, Fig. 1 species II).¹⁸

Pale yellow crystals of **2** are moisture-sensitive, but indefinitely stable in an inert gas atmosphere and can be heated above 270 °C without decomposition. **2** crystallizes solvent-free in the triclinic space group *P* $\bar{1}$ with one molecule in the unit cell and displays a *trans*-substituted centrosymmetric dimer with a planar Sb₂N₂ core protected by two bulky *t*BuAr* groups similar to the molecular structures of [XsB(μ -NMes*)]₂ X = F, Cl, Br, I; *trans*-[ClSb(μ -N*t*Bu)]₂.^{19,20} As expected the Sb atoms are trigonal

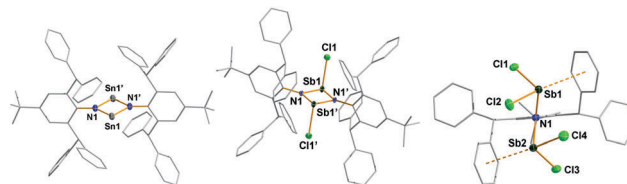
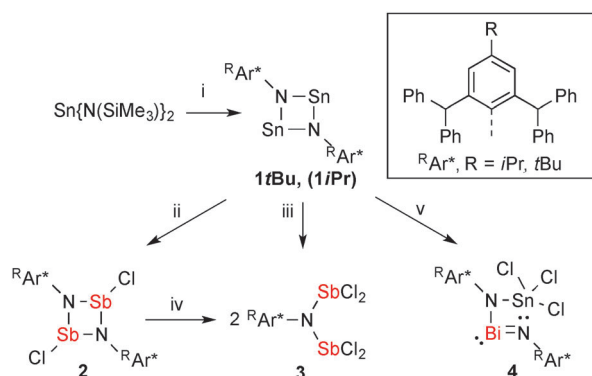


Fig. 2 Molecular structures of **1tBu** (left), **2** (middle) and **3** (right). Thermal ellipsoids drawn at 50% probability and –100 °C. *t*BuAr* substituents rendered as wire-frame and H atoms omitted for clarity. Selected bond lengths (Å) and angles (°) of **1tBu**: Sn1–N1 2.0752(16), 2.0897(16); N1–Sn1–N1' 78.22(6); **2**: Sb1–N1 2.033(2), Sb1–N1' 2.034(2), Sb1–Cl1 2.4327(7), Sb1Sb1 3.1749(3), N1–C1 1.430(3) Å, $\sum(\angle \text{Sb})$ 273.05; $\sum(\angle \text{N})$ 359.83, C1–C2–N1–Sb1 77.6(2); **3**: Sb1–N1 2.030(2), Sb1–Cl1 2.3709(7), Sb1–Cl2 2.4338(7), Sb2–N1 2.039(2), Sb2–Cl3 2.3731(7), Sb2–Cl4 2.4199(7), N1–C1 1.434(3), $\sum(\angle \text{Sb1})$ 280.08, $\sum(\angle \text{Sb2})$ 281.47, Sb1–N1–C1–C6 80.0(2).

pyramidally coordinated, with an s-type LP located on Sb and a trigonal planar coordination environment about the N atom. Additionally, one rather weak dipolar interaction between Sb and a flanking phenyl group (Sb...C_{ct} = 3.29 Å, C_{ct} = centroid) is detected (Fig. 2, left).²¹ The formation of **2** can be reproduced, however, if an excess of SbCl₃ is used, a new product *t*BuAr*N(SbCl₂)₂ (**3**) was isolated. Consequently, we reasoned that **3** was accessible directly from **1tBu** (reaction (iii) in Scheme 1) when combined with four equiv. of SbCl₃, which yielded pure **3**. Moreover, treatment of **2** with two additional equiv. of SbCl₃ also afforded (reaction (iv) in Scheme 1) **3** in good yields (78%). **3** is thermally stable and melts without decomposition at 236 °C and also shows distinct ¹H NMR shifts for the *p*-*t*Bu, the CHPh₂ and the inner phenyl H atoms. Furthermore, **3** belongs to the family of *N,N*-bis(dichloro-pnictino)amines, which are well documented for phosphorus (RN(PCl₂)₂, R = Dipp, Trip, Ph).² Compound **3** was found to be monoclinic (*P*₂₁/*n*) with one molecule of **3** and two disordered C₆H₅F solvent molecules in the asymmetric unit. The Sb–N distances of 2.030(2) and 2.039(2) Å are shorter than the sum of the covalent radii for Sb and N (*cf.* $\sum r_{\text{cov}}(\text{N–Sb}) = 2.11$ Å)²² representing highly polarized Sb–N single bonds. The trigonal planar N atom lies between both pyramidal SbCl₂ units, which adopt a *trans* configuration with respect to the SbCl₂ moieties (Fig. 2 right). Interestingly, two intramolecular Sb...Cl contacts (Sb1...Cl4, Sb2...Cl2 *ca.* 3.35 Å; *cf.* $\sum r_{\text{vdw}}(\text{N–Sb}) = 3.81$ Å),²³ stabilizing this *trans* configuration, but no intermolecular contacts are observed.

In addition, the reaction of **1tBu** with two equiv. of BiCl₃ was studied in CH₂Cl₂, resulting in a black reaction mixture (reaction (v) in Scheme 1). After multiple filtrations a clear orange solution was obtained. Recrystallization yielded small amounts of orange crystals that were identified as the hitherto unknown [BiSnCl₃(μ -N*t*BuAr*)₂] (**4**). The black residue could not be conclusively identified and we assume that elemental tin is formed in a complex redox process that might also involve the formation of elemental bismuth (*vide infra*). It has been shown before that the Sn(II) center in [Me₂SiSn(μ -N*t*Bu)]₂ acts as a chloride acceptor in the coupling of phosphalkenes²⁴ and in the reaction with chlorophosphanes.²⁵

Revision of the reaction conditions prompted us to repeat the experiment in C₆H₅F with one equivalent of BiCl₃



Scheme 1 Preparation of **1R-4**: (i) 2 RAr*NH₂, –2 HN(SiMe₃)₂, (ii) 2 SbCl₃, –2 SnCl₂, (iii) 4 SbCl₃, –2 SnCl₂, (iv) 2 SbCl₃, and (v) BiCl₃, –Sn.

(with respect to **1tBu**), to exclude a chloride-shift from CH_2Cl_2 . This again resulted after filtration over a celite-padded frit and concentration of the filtrate in the deposition of orange crystals of **4** as a $\text{C}_6\text{H}_5\text{F}$ solvate. Only small amounts of pure **4** could be isolated, therefore we cannot provide a comprehensive characterization. Nevertheless, the ^{119}Sn NMR spectrum of these isolated crystals revealed a signal at 115.5 ppm (Fig. S13, ESI[†]), which is in the expected range for a hypercoordinate $\text{N}_2\text{Sn}^{(\text{IV})}\text{Cl}_3$ moiety (cf. $\text{Me}_3\text{SnCl}_2^-$: 47.7, $\text{Me}_2\text{SnCl}_3^-$: 128 ppm, MeSnCl_4^- : 274 ppm).²⁶ It should be noted that ^{119}Sn NMR data strongly depend on substitution, coordination number and solvent giving rise to large chemical shift differences (cf. $[\text{SnCl}_3\{\text{k}^2\text{-DippN}(\text{H})\text{C}_2\text{H}_4\text{N}(\text{Dipp})\}]^-$ –303 ppm).²⁷ According to MO and NBO analyses of the truncated model $[\text{BiSnCl}_3(\mu\text{-NPh})_2]$, **4** can either be described as zwitterionic bisamally species (Lewis representation A/C in Fig. 4), as a bismuthenium species (E) or as an iminobismutane (B and D), and therefore represents the first neutral compound with a **4e–3c** double bond delocalized along N–Bi–N (Fig. 4). In addition, an s-type lone pair (93%, see Fig. S14 and S15, ESI[†]) is located at the Bi center. Lewis representations A/C represent the best Lewis structures according to NBO analysis. Along with structures of type E/F, which also possess a rather large weight, since the π bonds are dominantly located at the N atoms (81%), this situation resembles that of N-heterocyclic carbenes (NHC),²⁸ which are stabilized by intramolecular π -donor– π -acceptor interactions (population of the $p_z(\text{Bi}) = 0.47\text{e}$) to stabilize the dicoordinate carbene C atom. It should be noted that also Bi–N σ bonds (78%) are highly polar, as well as the Sn–Cl or Sn–N bonds (N, Cl: ca. 80%). The computed large positive charges at the Bi and Sn centers are very similar with values of +1.67 and 1.77e supporting the picture of highly polarized Bi–N and Sn–Y (Y = Cl, N) bonds.

4 crystallizes as CH_2Cl_2 solvate ($\text{4} \cdot (\text{CH}_2\text{Cl}_2)_2$) in the triclinic space group $P\bar{1}$ with two molecules of **4** and four CH_2Cl_2 molecules (disordered on their positions) in the cell. Moreover, from $\text{C}_6\text{H}_5\text{F}$ species **4** crystallizes as a solvate of fluorobenzene solvate ($\text{4} \cdot \text{C}_6\text{H}_5\text{F}$) in the orthorhombic space group $Pna2_1$ (the discussion is led for $\text{4} \cdot \text{CH}_2\text{Cl}_2$). The most prominent structural feature is the planar 4-membered Sn–N–Bi–N heterocycle featuring two different heavy main group metals (deviation from planarity < 2.3° , Fig. 3). Both Bi–N bond lengths are rather short with 2.106(3) and 2.108(3) Å (cf. $\sum r_{\text{cov}}(\text{N–Bi}) = 2.22$, $(\text{N}=\text{Bi}) = 2.01$ Å;²² $[\text{Me}_2\text{SiBi}(\mu\text{-NtBu})_2]^+$ 2.08 Å, $[\text{Bi}(\text{IBi})(\mu\text{-Nter})_2]^+$ 2.13 Å, and $[\text{Me}_2\text{SiBi}(\mu\text{-NDipp})_2]$ 2.12 Å, where Dipp = 2,6-iPrC₆H₃)^{4,5,29} clearly displaying some Bi–N double bond character in accord with our computation (Fig. 4). Interestingly, both Sn–N bond lengths (2.094(3) and 2.107(3) Å, cf. $\sum r_{\text{cov}}(\text{N–Sn}) = 2.11$, $(\text{N}=\text{Sn}) = 1.90$ Å) are in the similar range like the Bi–N distances, however, describing typical highly polarized Sn^(IV)–N single bonds. Both the N–Bi–N angle and N–Sn–N angles are rather acute with ca. 78° (cf. $[\text{Me}_2\text{SiBi}(\mu\text{-NtBu})_2]^+$ 72.9, $[\text{Bi}(\text{IBi})(\mu\text{-Nter})_2]^+$ 77.4°, and $[\text{Me}_2\text{SiBi}(\mu\text{-NDipp})_2]^+$ 73.7),^{4,5,29} while the two Bi–N–Sn angles are much larger with 101–102°. A closer look at the secondary interactions revealed that the Sn–N–Bi–N heterocycle is well protected inside the pocket formed by the two ^{tBu}Ar*–phenyl substituents. However, the dicoordinate bismuth is stabilized by strong secondary interactions (Menshutkin type π complexes)²¹

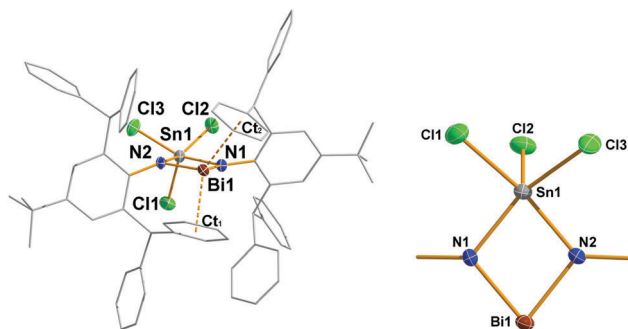


Fig. 3 Molecular structures of **4**. Thermal ellipsoids drawn at 50% probability and -100°C . ^{tBu}Ar* substituents rendered as wire-frame and H atoms omitted for clarity. Selected bond lengths (Å) and angles ($^\circ$) of **4**: Sn1–N1 2.094(3), Sn1–N2 2.107(3), Sn1–Cl1 2.353(1), Sn1–Cl3 2.387(1), Sn1–Cl2 2.403(1), Sn1···Bi1 3.2631(4), Bi1–N1 2.106(3), Bi1–N2 2.108(3), N1–C37 1.425(5), N2–C1 1.426(5), N1–Sn1–N2 78.41(12), N1–Bi1–N2 78.10(12), $\sum(\angle\text{N1})$ 358.0, $\sum(\angle\text{N2})$ 353.4, Bi1–C_{Ct1} 2.891, Bi1–C_{Ct2} 2.978 Å.

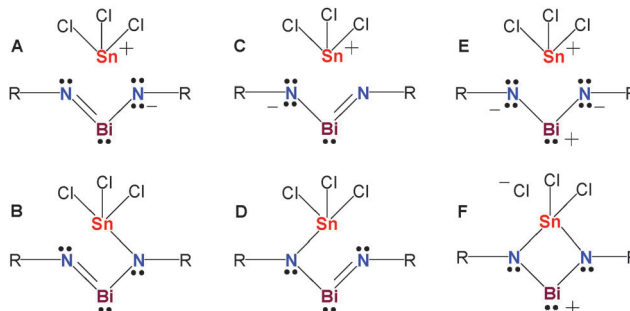


Fig. 4 Selected Lewis representations of **4**.

with two phenyl groups as indicated by very short Bi···centroid distances (2.891/2.978 Å; cf. $[\text{MeAr}^*\text{N}(\text{SiMe}_3)\text{BiCl}][\text{Al}(\text{OR}^F)_4]^+$ 2.86/2.94 Å)⁸ which are well within the range of van-der-Waals radii ($\sum r_{\text{vdw}}(\text{C} \cdots \text{Bi}) = 3.77$ Å).²³

In conclusion, we succeeded in the preparation of the first *N,N'*-bis(dichlorostibinino)amine and an unusual heterocycle containing Sn^(IV) and a dicoordinate Bi-center, which is protected by arene-interactions to flanking phenyl groups of the bulky Ar* moiety. These species might be useful starting materials for the preparation of pnictadiazonium salts of Sb and Bi. In comparison to stable N-heterocyclic carbenes,²⁸ the dicoordinated Bi species **4** can be regarded as a heavy atom analog of NHCs.

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Notes and references

- (a) G. He, O. Shynkaruk, M. W. Lui and E. Rivard, *Chem. Rev.*, 2014, **44**, 7815–7880; (b) M. S. Balakrishna, D. J. Eisler and T. Chivers, *Chem. Soc. Rev.*, 2007, **36**, 650–664.
- (a) F. Reiß, A. Schulz, A. Villinger and N. Weding, *Dalton Trans.*, 2010, **39**, 9962; (b) C. Ganesamoorthy, M. S. Balakrishna, J. T. Mague and H. M. Tuononen, *Inorg. Chem.*, 2008, **47**, 7035–7047; (c) N. Burford, C. T. Stanley, K. D. Conroy, B. Ellis, C. L. B. MacDonald, R. Ovens,



- A. D. Phillips, P. Ragona and D. Walsh, *Can. J. Chem.*, 2002, **80**, 1404–1409; (d) V. D. Romanenko, A. B. Drapailo, A. N. Chernega and L. N. Markovskii, *Zh. Obshch. Khim.*, 1991, **61**, 2434–2441; (e) S. Goldschmidt and H.-L. Krauß, *Liebigs Ann. Chem.*, 1955, **595**, 193–202.
- 3 D. Michalik, A. Schulz and A. Villinger, *Angew. Chem., Int. Ed.*, 2010, **46**, 7575–7577 (*Angew. Chem.*, 2010, **122**, 7737–7740).
- 4 M. Veith, B. Bertsch and V. Huch, *Z. Anorg. Allg. Chem.*, 1988, **559**, 73–88.
- 5 M. Lehmann, A. Schulz and A. Villinger, *Angew. Chem., Int. Ed.*, 2012, **51**, 8087–8091 (*Angew. Chem.*, 2012, **124**, 8211–8215).
- 6 (a) D. Michalik, A. Schulz, A. Villinger and N. Weding, *Angew. Chem., Int. Ed.*, 2008, **47**, 6465–6468 (*Angew. Chem.*, 2008, **120**, 6565–6568); (b) A. Schulz and A. Villinger, *Inorg. Chem.*, 2009, **48**, 7359–7367.
- 7 (a) T. Beweries, R. Kuzora, U. Rosenthal, A. Schulz and A. Villinger, *Angew. Chem., Int. Ed.*, 2011, **50**, 8974–8978 (*Angew. Chem.*, 2011, **123**, 9136–9140); (b) S. Demeshko, C. Godemann, R. Kuzora, A. Schulz and A. Villinger, *Angew. Chem., Int. Ed.*, 2013, **52**, 2105–2108 (*Angew. Chem.*, 2013, **125**, 2159–2162); (c) A. Hinz, A. Schulz and A. Villinger, *Chem. – Eur. J.*, 2014, **20**, 3913–3916; (d) A. Hinz, R. Kuzora, A. Schulz and A. Villinger, *Chem. – Eur. J.*, 2014, **20**, 14659–16673; (e) A. Hinz, A. Schulz and A. Villinger, *Chem. Commun.*, 2015, **51**, 1363–1366.
- 8 C. Hering-Junghans, M. Thomas, A. Schulz and A. Villinger, *Chem. – Eur. J.*, 2015, **21**, 6713–6717.
- 9 J. Li, A. Stasch, C. Schenk and C. Jones, *Dalton Trans.*, 2011, **40**, 10448–10456.
- 10 J. Li, C. Schenk, F. Winter, H. Scherer, N. Trapp, A. Higelin, S. Keller, R. Pöttgen, I. Krossing and C. Jones, *Angew. Chem., Int. Ed.*, 2012, **51**, 9557–9561 (*Angew. Chem.*, 2012, **124**, 9695–9699).
- 11 J. Li, C. Schenk, C. Goedecke, G. Frenking and C. Jones, *J. Am. Chem. Soc.*, 2011, **133**, 18622–18625.
- 12 T. J. Hadlington and C. Jones, *Chem. Commun.*, 2014, **50**, 2321.
- 13 (a) T. J. Hadlington, M. Hermann, J. Li, G. Frenking and C. Jones, *Angew. Chem., Int. Ed.*, 2013, **52**, 10199–10203 (*Angew. Chem.*, 2013, **125**, 10389–10393); (b) T. J. Hadlington, M. Hermann, G. Frenking and C. Jones, *J. Am. Chem. Soc.*, 2014, **136**, 3028–3031.
- 14 D. Dange, A. Davey, J. A. B. Abdalla, S. Aldridge and C. Jones, *Chem. Commun.*, 2015, **51**, 7128–7131.
- 15 W. A. Merrill, R. J. Wright, C. S. Stanciu, M. M. Olmstead, J. C. Fettinger and P. P. Power, *Inorg. Chem.*, 2010, **49**, 7097–7105.
- 16 M. Brela, A. Michalak, P. P. Power and T. Ziegler, *Inorg. Chem.*, 2014, **53**, 2325–2332.
- 17 M. Veith, *Angew. Chem., Int. Ed. Engl.*, 1975, **14**, 265–266 (*Angew. Chem.*, 1975, **87**, 287–288).
- 18 M. Veith and B. Bertsch, *Z. Anorg. Allg. Chem.*, 1988, **557**, 7–22.
- 19 M. Lehmann, A. Schulz and A. Villinger, *Eur. J. Inorg. Chem.*, 2010, 5501–5508.
- 20 D. J. Eisler and T. Chivers, *Inorg. Chem.*, 2006, **45**, 10734–10742.
- 21 H. Schmidbaur and A. Schier, *Organometallics*, 2008, **27**, 2361–2395.
- 22 P. Pyykkö and M. Atsumi, *Chem. – Eur. J.*, 2009, **15**, 12770–12779.
- 23 M. Mantina, A. C. Chamberlin, R. Valero, C. J. Cramer and D. G. Truhlar, *J. Phys. Chem. A*, 2009, **113**, 5806–5812.
- 24 E. Niecke, H. J. Metternich and R. Streubel, *Eur. J. Inorg. Chem.*, 1990, 67–69.
- 25 J. K. West and L. Stahl, *Organometallics*, 2012, **31**, 2042–2052.
- 26 (a) P. J. Smith and A. P. Tupciauskas, *Annu. Rep. NMR Spectrosc.*, 1978, **8**, 291; (b) G. F. Hewitson, Master thesis, Durham University, 1980; (c) J. Ortera, *J. Org. Chem.*, 1981, **221**, 57.
- 27 S. M. Mansell, C. A. Russell and D. F. Wass, *Dalton Trans.*, 2015, **44**, 9756–9765.
- 28 (a) D. Bourissou, O. Guerret, F. P. Gabbaï and G. Bertrand, *Chem. Rev.*, 2000, **100**, 39–92; (b) N. Marion and S. P. Nolan, *Acc. Chem. Res.*, 2008, **41**, 1440–1449; (c) D. Bézier, J.-B. Sortais and C. Darcel, *Adv. Synth. Catal.*, 2013, **355**, 19–33.
- 29 R. J. Schwamm, B. M. Day, M. P. Coles and C. M. Fitchett, *Inorg. Chem.*, 2014, **53**, 3778.

