ISSN 1070-3284, Russian Journal of Coordination Chemistry, 2019, Vol. 45, No. 10, pp. 728–733. © Pleiades Publishing, Ltd., 2019.
Russian Text © The Author(s), 2019, published in Koordinatsionnaya Khimiya, 2019, Vol. 45, No. 10, pp. 635–640.

Cleavage of B–C Bonds and Anion $[PhBH_3]^-$ Formation in the Reaction of the Yb(II) Hydride Complex with BPh_3

D. M. Lyubov[a], I. V. Basalov[a], A. S. Shavyrin[a], A. V. Cherkasov[a], and A. A. Trifonov[a, b, *]

[a] *Razuvaev Institute of Organometallic Chemistry, Russian Academy of Sciences, Nizhny Novgorod, Russia*
[b] *Nesmeyanov Institute of Organoelement Compounds, Russian Academy of Sciences, Moscow, Russia*
**e-mail: trif@iomc.ras.ru*

Received March 28, 2019; revised April 4, 2019; accepted April 22, 2019

Abstract—The reaction of the amidinatehydride complex of divalent ytterbium $[(Amd)Yb^{II}(\mu^2\text{-}H)]_2$ (Amd is {*tert*-BuC(NC_6H_3-*iso*-Pr_2-2,6$)_2$}) with BPh_3 proceeds with the cleavage of the B–C bonds and affords the Yb(II)$[(Amd)Yb^{II}(\mu^2\text{-}H_3BPh)]_2$ complex containing the phenyltrihydroborate anion $[PhBH_3]^-$. The X-ray diffraction analysis (CIF file CCDC no. 1902290) shows that the $[PhBH_3]^-$ anions in the complex are bridging. The “nonclassical” κ^1-amido-η^6-arene coordination mode to the Yb^{2+} ion is retained for the amidinate ligand.

Keywords: lanthanides, hydride complexes, synthesis, structure, reactivity

DOI: 10.1134/S1070328419100026

INTRODUCTION

The unique reactivity of the hydride complexes of lanthanides in stoichiometric reactions along with a remarkable catalytic activity in the whole series of transformations of unsaturated substrates powerfully stimulated the development of this area of chemical science [1–7]. The first reports on the synthesis of bis(cyclopetadienyl)monohydride lanthanide derivatives appeared in the 1980s [8–10]. Their dihydride analogs of the semisandwich type have been synthesized later [11–15]. Many monohydride [16–20], dihydride [21–29], cationic hydride [30–34], and alkylhydride [35–40] derivatives of rare-earth metals stabilized by non-cyclopentadienyl ligands of various types [41–43] are presently known. However, all these successes in the area of hydride chemistry concern the derivatives of trivalent lanthanides, whereas the hydride complexes of these metals in the divalent state are still rare and their reactivity remains almost unstudied.

Only three hydride complexes of lanthanides in the oxidation state +2 are presently known. The first example [44] is the hydride complex [(Tp-*tert*-Bu)Yb(μ^2-H)$]_2$ (Tp-*tert*-Bu is HB(C_3HN_2-*tert*-Bu-3-Me-5$)_3$) stabilized by the bulky tris(pyrazolyl)borate ligand. The reactivity of this compound was studied in a series of stoichiometric reactions with CH acids (terminal acetylenes, dipivaloylmethane, and substituted cyclopentadiene), and the possibility of the addition of the Yb–H bonds to the multiple C–C and C–O bonds was demonstrated [44]. The hydride complex [{HC(C(Me)NC_6H_3-*iso*-Pr_2-2,6$)_2$}Yb(μ^2-H)-(THF)$]_2$ containing the bulky β-diketiminate ligand was synthesized [45] and turned out to be an active catalyst for olefin hydrosilylation. The data on the synthesis of the amidinatehydride complex $[(Amd)Yb(\mu^2\text{-}H)]_2$ (**I**), where Amd is {*tert*-BuC-(NC_6H_3-*iso*-Pr_2-2,6$)_2$} [46], were published. This complex demonstrates the “nonclassical” κ^1-amido-η^6-arene coordination mode to the Yb^{2+} ion with the surprisingly stable Yb(II)–η^6-arene interaction. It is shown for the reactions of the $[(Amd)Yb(\mu^2\text{-}H)]_2$ hydride complex with the one-electron oxidants that the hydride ligand is a stronger reducing agent than the Yb^{2+} ion [46, 47]. The first cationic Yb(II) hydride complexes $[(Me_4TACD)Yb(\mu\text{-}H)]_2^{2+}[BAr_4]_2^-$ (Me_4TACD is 1,4,7,10-tetramethyl-1,4,7,10-tetraazacyclododecane) have been prepared quite recently [48] and turned out to be efficient catalysts for the hydrogenation and hydrosilylation of hex-1-ene and for the exchange between H_2 and D_2 [48].

However, the main properties of the Yb(II)–H bond remain nearly unstudied. In this work, we studied the reaction of the dimeric hydride complex Yb(II) $[(Amd)Yb(\mu^2\text{-}H)]_2$ with Lewis acid BPh_3 in order to elucidate the capability of the hydride anion in the lanthanide complexes of coordinating to Lewis acids as a possible synthetic approach to the “cleavage” of their dimeric structure and of forming monomeric hydride particles. This reaction proceeds with the cleavage of the C–B bonds and affords the dimeric complex $[(Amd)Yb^{II}(\mu^2\text{-}H_3BPh)]_2$ containing the bridging phenyltrihydroborate anions.

EXPERIMENTAL

The complexes were synthesized under the conditions excluding contact with air oxygen and moisture using the standard Schlenk procedure. Toluene was dried over sodium benzophenone ketyl, and hexane was dehydrated over metallic sodium and then thoroughly degassed and condensed in vacuum to the reaction ampule prior to use. Complex **I** was synthesized using the published procedure [46].

Synthesis of $[(Amd)Yb(\mu\text{-}H_3BPh)]_2$ (II). A solution of BPh_3 (0.163 g, 0.674 mmol) in toluene (10 mL) was added with stirring to compound **I** (0.400 g, 0.337 mmol) in toluene (20 mL). The reaction mixture was stirred at room temperature for 3 h. The color of the solution changed from dark violet to dark red. Toluene was removed in vacuo, and hexane (20 mL) was added to the solid residue. The insoluble residue was separated from the products soluble in hexane by centrifugation and was dissolved in a fresh portion of toluene. The slow centrifugation of the obtained solution in toluene at room temperature resulted in the formation of red-brown crystals of complex **II**. The mother liquor was decanted, and the crystals were dried in vacuo for 20 min. The yield of complex **II** was 0.070 g (15%). The hexane solution was concentrated at room temperature to give emerald-green crystals of the $(Amd)_2Yb$ complex (**III**) in a yield of 0.068 g (10% based on the amount of the metal taken for the reaction).

For $C_{70}H_{102}B_2N_4Yb_2$ (*FW* = 1367.32)

Anal. calcd., %	C, 61.49	H, 7.52	N, 4.10	Yb, 25.31
Found, %	C, 61.88	H, 7.79	N, 4.01	Yb, 24.87

^1H NMR for complex **II** (400 MHz, benzene-d_6, 293 K), δ, ppm: 0.92 (br.s, 18H, C*H*-*tert*-Bu), 1.34 (m, 24H, CH_3-*iso*-Pr), 1.60–2.23 (br.m, 6H, BH_3), 3.11 (m, 2H, CH-*iso*-Pr), 3.41 (m, 2H, CH-*iso*-Pr), 6.90–7.32 (m, 22H, C*H*Ar and BPh). $^{13}C\{^1H\}$ NMR for complex **II** (100 MHz, benzene-d_6, 293 K), δ, ppm: 20.4 (s, *C*H_3-*iso*-Pr), 23.0 (s, *C*H_3-*iso*-Pr), 26.0 (s, *C*H_3-*iso*-Pr), 28.4 (s, *C*H-*iso*-Pr), 29.5 (s, *C*H_3-*iso*-Pr), 31.5 (s, *C*H_3-*tert*-Bu), 42.7 (s, *C*-*tert*-Bu), 118.6 (s, *C*HAr), 123.0 (s, *C*HAr), 123.5 (s, *C*HAr), 124.2 (s, *C*HAr), 126.2 (br.s, *C*HBPh), 133.0 (br.s, *C*HBPh), 137.7 (br.s, *C*HBPh), 142.5 (s, *C*Ar), 143.4 (s, *C*Ar), 144.2 (s, *C*Ar), 145.7 (br.s, *C*BPh), 147.6 (s, *C*Ar), 169.8 (s, N*C*N). $^{11}B\{^1H\}$ NMR for complex **II** (128.4 MHz, benzene-d_6, 293 K), δ, ppm: –21.0.

^1H and $^{13}C\{^1H\}$ NMR spectra were recorded on Bruker DPX 200 MHz and Bruker Avance III 400 MHz instruments. Chemical shifts are presented in ppm relative to the known shifts of residual protons of the deuterated solvents. 2D ^{11}B–^1H correlation experiments were carried out using the *ge*-HSQC sequence (hsqcetgp) with the parameters optimized for the ^{11}B–^1H experiment. Elemental analysis was carried out on a Perkin-Elmer Series II CHNS/O Analyser 2400 instrument. The content of lanthanide was determined by complexonometric titration (Trilon B) using Xylenol Orange as the indicator.

The X-ray diffraction analysis of a single-crystal sample of compound **II** (0.25 × 0.21 × 0.09 mm) was carried out on a Bruker Smart Apex diffractometer (MoK_α radiation, $\lambda = 0.71073$ Å, ω scan mode, $T = 100$ K, $\theta = 1.71°–26.04°$). Experimental sets of intensities were measured and integrated, an absorption correction was applied, and the structures were refined using the Smart [49], SADABS [50], and SHELX [51] program packages. The crystals of compound **II** ($C_{70}H_{102}B_2N_4Yb_2$, *FW* = 1367.25) were monoclinic, space group $P2_1/n$, $a = 10.8191(5)$, $b = 14.7527(7)$, $c = 20.3110(10)$ Å, $\beta = 92.7530(10)°$, $V = 3238.1(3)$ Å^3, $Z = 2$, $\rho_{calcd} = 1.402$ g/cm^3, $\mu = 2.913$ mm^{-1}. The total number of measured reflections was 27388, and 6383 independent reflections ($R_{int} = 0.0351$) were used for the refinement of 372 parameters of the structure by full-matrix least squares for F^2_{hkl} in the anisotropic approximation for non-hydrogen atoms. The hydrogen atoms of the phenyltrihydroborate groups were found from the difference Fourier electron density synthesis and refined with geometric restraints (the B–H and H···H distances were equalized using the DFIX and SADI instructions). Other hydrogen atoms were placed in the geometrically calculated positions. All hydrogen atoms were refined isotropically with the fixed thermal parameters $U(H)_{iso} = 1.2U(C)_{eq}$ ($U(H)_{iso} = 1.5U(C)_{eq}$ for the methyl groups). After the final refinement, $wR_2 = 0.0695$ and $S(F^2) = 1.028$ for all reflections ($R_1 = 0.0274$ for 5048 reflections satisfying the condition $I > 2\sigma(I)$). The residual maximum and minimum of the electron density were 1.51/–0.44 e/Å^3.

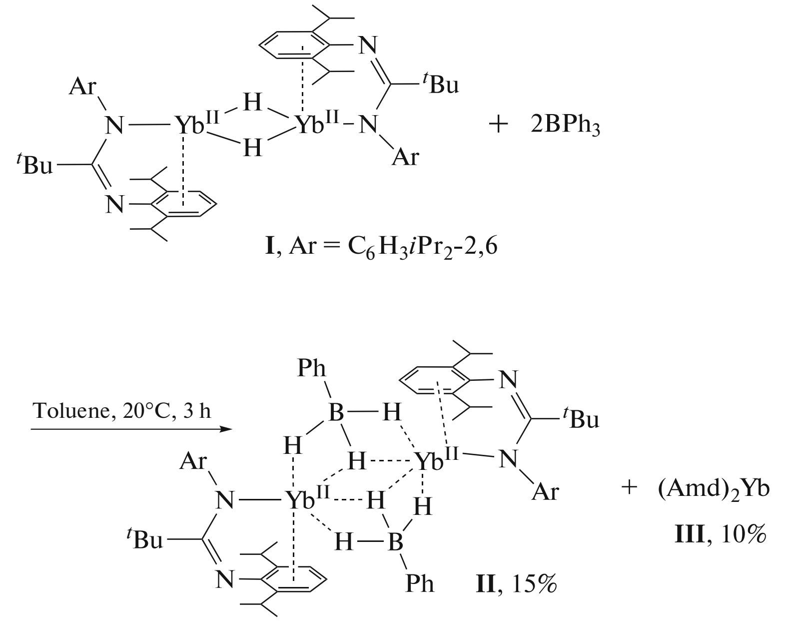
The structure of compound **II** was deposited with the Cambridge Crystallographic Data Centre (CIF file CCDC no. 1902290; ccdc.cam.ac.uk/getstructures).

RESULTS AND DISCUSSION

The most part of the presently known hydride derivatives of rare-earth metals in the oxidation states both +3 and +2 are dimeric or cluster compounds because of the easy formation of the Ln–H–Ln bridging bonds. The nuclearity of the hydride derivatives of rare-earth metals is primarily determined by the steric parameters of the "auxiliary" ligand environment. Moreover, the use of the bulky cyclopentadienyl ligands made it possible to synthesize a series of monomeric hydride derivatives Cp_2LnH (Cp is C_5H_2-

tert-Bu_3 [3, 52], and $C_5Me_4SiMe_3$ [53, 54]). It was also shown that the dissociation of the dimeric fragments Ln_2H_2 can occur under the action of Lewis acids [55, 56]. The dissociation of the dimeric complex to the monomeric derivatives due to the coordination of the Ln–H bond to the Lewis acid can be an alternative method for the preparation of the monomeric hydride compounds. It has previously been shown that the monomeric cerium hydride complex $[C_5H_2$-*tert*-$Bu_3]_2CeH$ in a solution can reversibly react with such a Lewis acid as triphenylboron [52].

The reaction of dimeric hydride complex **I** with two equivalents of triphenylboron BPh_3 was carried out to obtain the monomeric Yb(II) hydride complex and to study the reactivity of the Yb–H bond toward the Lewis acids. The reaction was conducted in toluene at room temperature (Scheme 1). The new Yb(II) amidinate complex (**II**) containing the bridging phenyltrihydroborate anions $[PhBH_3]^-$ was established to be the reaction product. Interestingly, the reaction does not stop at the interaction of the Lewis acid and base but occurs more deeply with the C–B bond cleavage, transfer of the hydride anions, and formation of the $[PhBH_3]^-$ anion. The Yb(II) bis(amidinate) complex (**III**) [46] was also found among the reaction products and isolated as emerald-green crystals in a yield of 10%. The formation of bis(amidinate) derivative **III** can be a consequence of the disproportionation of the heteroligand Yb(II) complexes formed during the reaction. We failed to isolate other ytterbium-containing products from the reaction mixture.



Scheme 1.

The single-crystal samples of complex **II** suitable for X-ray diffraction analysis were obtained by the slow concentration of a solution of complex **II** in toluene at room temperature. According to the X-ray diffraction data, a molecule of complex **II** in the crystal cell exists in the partial position at the inversion center. Thus, the crystal cell contains two molecules of the complex. Selected bond lengths and bond angles are given in Table 1. Complex **II** is a dimer (Fig. 1) in which two amidinatiteytterbium moieties (Amd)Yb are linked by two bridging phenyltrihydroborate anions $[PhBH_3]^-$. In the earlier known complexes of transition *d* metals (Ti, Zr [57–59], Ru [60], and Ir [61]), the phenyltrihydroborate ligands are terminal and linked with transition metal ions through two or three hydride atoms, whereas the bridging coordination of the $[PhBH_3]^-$ anions leading to dimer formation was earlier found in the lithium complexes [62, 63].

The Yb–B distances (2.749(4) and 2.898(4) Å) in complex **II** are substantially longer than the corresponding distances in the Yb(II) borohydride derivatives containing the terminal borohydride group BH_4^-: $[(DIP_2Pyr)Yb(BH_4)(THF)_3]$ (Yb–B 2.595(9) Å) [64], $[(Tp$-*tert*-$Bu)Yb(BH_4)(THF)]_2$ (Yb–B 2.596(5) Å) [65], $[(Dipp)_2NacNacYb(BH_4)(THF)_2]$ (Yb–B 2.576(8) Å) [66], and $[\{CH(PPh_2{=}NSiMe_3)\text{-}(PPh_2{=}S)\}Yb(BH_4)(THF)_2]$ (Yb–B 2.611(7) Å) [67]. Moreover, the Yb–B distances in complex **II** exceed the corresponding values found for the Yb(II) (cyclooctane-1,5-diyl)dihydroborate derivatives $Yb\{[(\mu\text{-}H)_2BC_8H_{14}]_2K(Solv)_n\}_2$ (Yb–B 2.703(5)–2.738(5) Å) [68] in which the (cyclooctane-1,5-dilyl)dihydroborate groups $[C_8H_{14}BH_2]^-$ are bridging between the

Table 1. Selected bond lengths (*d*) and bond angles (ω) in complex **II**

Bond	*d*, Å
Yb(1)–N(1)	2.377(3)
Yb(1)–B(1)	2.749(4)
Yb(1)–B(1*A*)	2.898(4)
N(1)–C(1)	1.359(4)
N(2)–C(1)	1.313(4)
Yb(1)···Yb(1*A*)	4.0418(3)
Yb(1)–C(18)	2.750(3)
Yb(1)–C(19)	2.798(3)
Yb(1)–C(20)	2.853(3)
Yb(1)–C(21)	2.868(3)
Yb(1)–C(22)	2.870(3)
Yb(1)–C(23)	2.835(3)
B(1)–C(30)	1.579(5)
Angle	**ω, deg**
Yb(1)B(1)Yb(1*A*)	91.4(2)
B(1)Yb(1)B(1*A*)	88.6(2)
N(1)C(1)N(2)	119.8(3)

Yb^{2+} and potassium ions. The Yb–H distances in compound **II** lie in a wide range of 2.22(3)–2.57(3) Å. The presence of more bulky bridging $[PhBH_3]^-$ anions in compound **II** elongates the distance between the metal cations (Yb···Yb 4.0418(3) Å) in the dimer compared to the initial hydride **I** (Yb···Yb 3.3553(4) Å). However, the "nonclassical" κ^1-amido,-η^6-areno coordination mode of the amidinate ligand is retained. The Yb–N bond (2.377(3) Å) and Yb–C_{aryl} (2.750(3)–2.870(3) Å) and Yb–Ar_{center} (2.458(2) Å) distances in complex **II** are somewhat longer than those in the initial hydride **I** (Yb–N 2.329(3) Å, Yb–C_{aryl} 2.696(2)–2.838(2) Å, Yb–Ar_{center} 2.410(5) Å) and comparable to the distances in the earlier known Yb(II) amidinate complexes in which the coordination of the amidinate ligands via the κ^1-amido,-η^6-arene mode is observed [46, 47, 69–71].

The ^{1}H NMR spectrum of complex **II** recorded in a benzene-d_6 solution at 293 K contains signals attributed to the amidinate ligand and phenyltrihydroborate anion. The signals of the hydride atoms of the $[PhBH_3]^-$ ligand appear as a broadened multiplet consisting of four signals in a range of 1.60–2.23 ppm. These chemical shifts are comparable to the values observed in the spectra of the related Ti and Zr complexes of the mono- and bis(cyclopentadienyl) series ($\delta_H(BH_3)$ = 1.39 ppm for $Cp_2Zr(PhBH_3)_2$, 2.28 ppm for $CpZr(PhBH_3)_3$, and 2.37 ppm for $Cp_2ZrCl(PhBH_3)$) [57, 59]. In order to more reliably identify the signals observed in the ^{1}H and ^{11}B NMR signals, we recorded the 2D ^{11}B–^{1}H*ge*-HSQC NMR spectrum exhibiting the cross peak (–21.0, 1.90). The multiplic-

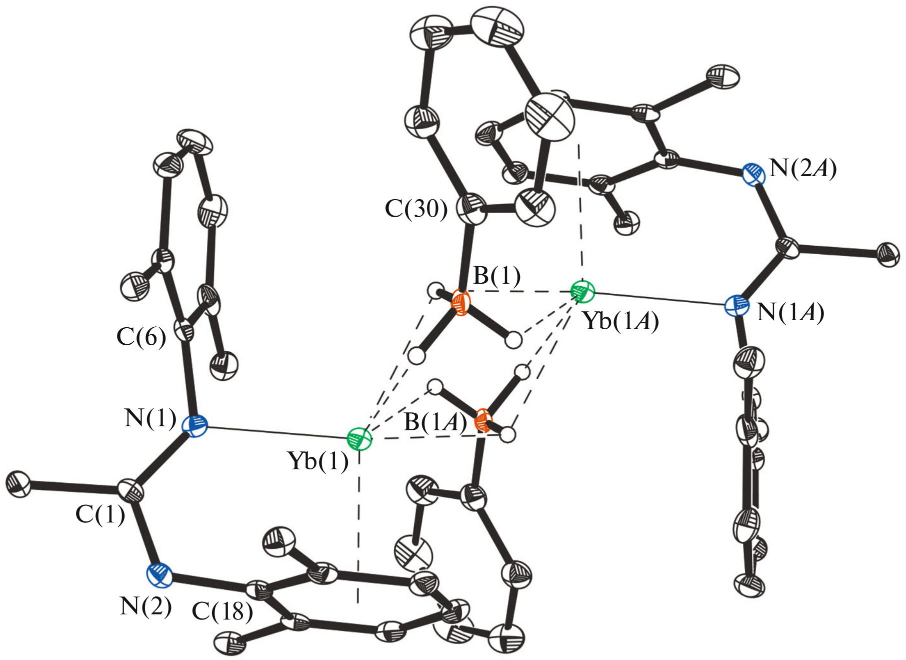


Fig. 1. Molecular structure of complex **II**. Thermal ellipsoids are presented with 30% probability. The methyl fragments of the 2,6-diisopropylphenyl and *tert*-butyl substituents and all hydrogen atoms, except for the hydrogen atoms of the phenyltrihydroborate groups, are omitted for clarity.

ity of the hydride signal was refined using the $^{11}B-{}^1H$*ge*-HSQC NMR spectrum without broad band decoupling. The presence of four lines in the multiplet is well consistent with that expected for the splitting of three protons on one ^{11}B (the spin of the protons is 1/2, and the spin of the ground boron isotope is 3/2).

Thus, it is found that the reaction of the hydride complex of divalent ytterbium (**I**) stabilized by the bulky amidinate ligand with Lewis acid BPh_3 is accompanied by the cleavage of the C–B bonds and the reduction of the complex to the phenyltrihydroborate anion $[PhBH_3]^-$. The reaction product is Yb(II) amidinate complex **II** in which two (Amd)Yb fragments are bound by two bridging phenyltrihydroborate anions.

ACKNOWLEDGMENTS

The X-ray diffraction studies were carried out using the scientific equipment of the Center for Collective Use “Analytical Center of the Razuvaev Institute of Organometallic Chemistry of the Russian Academy of Sciences.”

FUNDING

The X-ray diffraction studies were carried out in the framework of the state task.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

1. Ringelberg, S.N., Meetsma, A., Hessen, B., et al., *J. Am. Chem. Soc.*, 1999, vol. 121, p. 6082.
2. Werkema, E.L., Messines, E., Perrin, L., et al., *J. Am. Chem. Soc.*, 2005, vol. 127, p. 7781.
3. Maron, L., Werkema, E.L., Perrin, L., et al., *J. Am. Chem. Soc.*, 2005, vol. 127, p. 279.
4. Jeske, G., Lauke, H., Mauermann, H., et al., *J. Am. Chem. Soc.*, 1985, vol. 107, p. 8111.
5. Conticello, V.P., Brard, L., Giardello, M.A., et al., *J. Am. Chem. Soc.*, 1992, vol. 114, p. 2761.
6. Molander, G.A. and Romero, J.A.C., *Chem. Rev.*, 2002, vol. 102, p. 2161.
7. Oyamada, J., Nishiura, M., and Hou, Z., *Angew. Chem., Int. Ed. Engl.*, 2011, vol. 50, p. 10720.
8. Evans, W.J., Meadows, J.H., Wayda, A.L., et al., *J. Am. Chem. Soc.*, 1982, vol. 104, p. 2008.
9. Evans, W.J., Meadows, J.H., and Wayda, A.L., *J. Am. Chem. Soc.*, 1982, vol. 104, p. 2015.
10. Evans, W.J., Bloom, I., Hunter, W.E., et al., *J. Am. Chem. Soc.*, 1983, vol. 105, p. 1403.
11. Hou, Z., Zhang, Y., Tardif, O., et al., *J. Am. Chem. Soc.*, 2001, vol. 123, p. 9216.
12. Tardif, O., Nishiura, M., and Hou, Z., *Organometallics*, 2003, vol. 22, p. 1171.
13. Cui, D., Tardif, O., and Hou, Z., *J. Am. Chem. Soc.*, 2004, vol. 126, p. 1312.
14. Hou, Z., Nishiura, M., and Shima, T., *Eur. J. Inorg. Chem.*, 2007, p. 2535.
15. Nishiura, M. and Hou, Z., *Nature Chem.*, 2010, vol. 2, p. 257.
16. Hagadorn, J.R. and Arnold, J., *Organometallics*, 1996, vol. 15, p. 984.
17. Duchateau, R., van Wee, C.T., Meetsma, A., et al., *Organometallics*, 1996, vol. 15, p. 2279.
18. Trifonov, A.A., Skvortsov, G.G., Lyubov, D.M., et al., *Chem.-Eur. J.*, 2006, vol. 12, p. 5320.
19. Kissel, A.A., Mahrova, T.V., Lyubov, D.M., et al., *Dalton Trans.*, 2015, vol. 44, p. 12137.
20. Skvortsov, G.G., Tolpyguin, A.O., Fukin, G.K., et al., *Eur. J. Inorg. Chem.*, 2010, p. 1655.
21. Rong, W., He, D., Wang, M., et al., *Chem. Commun.*, 2015, vol. 51, p. 5063.
22. Cheng, J., Saliu, K., Kiel, G.Y., et al., *Angew. Chem., Int. Ed. Engl.*, 2008, vol. 47, p. 4910.
23. Cheng, J., Ferguson, M.F., and Takats, J., *J. Am. Chem. Soc.*, 2010, vol. 132, p. 2.
24. Cheng, J., Saliu, K., Ferguson, M.J., et al., *J. Organomet. Chem.*, 2010, vol. 695, p. 2696.
25. Cheng, J., Shima, T., and Hou, Z., *Angew. Chem., Int. Ed. Engl.*, 2011, vol. 50, p. 1857.
26. Johnson, K.R.D., Kamenz, B.L., and Hayes, P.G., *Organometallics*, 2014, vol. 33, p. 3005.
27. Ohashi, M., Konkol, M., Del Rosal, I., et al., *J. Am. Chem. Soc.*, 2008, vol. 130, p. 6920.
28. Zhou, J., Chu, J., Zhang, Y., et al., *Angew. Chem., Int. Ed. Engl.*, 2013, vol. 52, p. 4243.
29. Martin, D., Kleemann, J., Abinet, E., et al., *Eur. J. Inorg. Chem.*, 2013, p. 3987.
30. Lyubov, D.M., Doring, C., Ketkov, S.Yu., et al., *Chem.-Eur. J.*, 2011, vol. 17, p. 3824.
31. Fegler, W., Venugopal, A., Spaniol, T.P., et al., *Angew. Chem., Int. Ed. Engl.*, 2013, vol. 52, p. 7976.
32. Venugopal, A., Fegler, W., Spaniol, T.P., et al., *J. Am. Chem. Soc.*, 2011, vol. 133, p. 17574.
33. Arndt, S., Kramer, M.U., Fegler, W., et al., *Organometallics*, 2015, vol. 34, p. 3739.
34. Abinet, E., Martin, D., Standfuss, S., et al., *Chem.-Eur. J.*, 2011, vol. 11, p. 15014.
35. Li, X., Baldamus, J., and Hou, Z., *Angew. Chem., Int. Ed. Engl.*, 2005, vol. 44, p. 962.
36. Lyubov, D.M., Doring, C., Fukin, G.K., et al., *Organometallics*, 2008, vol. 27, p. 2905.
37. Lyubov, D.M., Fukin, G.K., Cherkasov, A.V., et al., *Organometallics*, 2009, vol. 28, p. 1227.
38. Luconi, L., Lyubov, D.M., Bianchini, C., et al., *Eur. J. Inorg. Chem.*, 2010, p. 608.
39. Lyubov, D.M., Cherkasov, A.V., Fukin, G.K., et al., *Dalton Trans.*, 2014, vol. 43, p. 14450.
40. Lyubov, D.M., Cherkasov, A.V., Fukin, G.K., et al., *Organometallics*, 2016, vol. 35, p. 126.
41. Trifonov, A.A., *Russ. Chem. Rev.*, 2007, vol. 76, p. 1049.

42. Trifonov, A.A. and Lyubov, D.M., *Coord. Chem. Rev.*, 2017, vol. 340, p. 10.
43. Abakumov, G.A., Piskunov, A.V., Cherkasov, V.K., et al., *Russ. Chem. Rev.*, 2018, vol. 87, p. 393.
44. Ferrence, G.M., McDonald, R., and Takats, J., *Angew. Chem., Int. Ed. Engl.*, 1999, vol. 38, p. 2233.
45. Ruspic, C., Spielman, J., and Harder, S., *Inorg. Chem.*, 2007, vol. 46, p. 5320.
46. Basalov, I.V., Lyubov, D.M., Fukin, G.K., et al., *Angew. Chem., Int. Ed. Engl.*, 2012, vol. 52, p. 3444.
47. Basalov, I.V., Lyubov, D.M., Fukin, G.K., et al., *Organometallics*, 2013, vol. 32, p. 1507.
48. Schuhknecht, D., Truong, K.-N., Spaniol, T.P., et al., *Chem. Commun.*, 2018, vol. 54, p. 11280.
49. *Smart*, Madison: Bruker AXS Inc., 2012.
50. Krause, L., Herbst-Irmer, R., Sheldrick, G.M., et al., *J. Appl. Crystallogr.*, 2015, vol. 48, p. 30.
51. Sheldrick, G.M., *Acta Crystallogr., Sect. C: Struct. Chem.*, 2015, vol. 71, p. 3.
52. Werkema, E.L., Andersen, R.A., Yahia, A., et al., *Organometallics*, 2009, vol. 28, p. 3173.
53. Summerscales, O.T., Batista, E.R., Scott, R.L., et al., *Eur. J. Inorg. Chem.*, 2016, p. 4551.
54. Takenaka, Y. and Hou, Z., *Organometallics*, 2009, vol. 28, p. 5196.
55. Lyubov, D.M., Bubnov, A.M., Fukin, G.K., et al., *Eur. J. Inorg. Chem.*, 2008, p. 2090.
56. Cheng, J. and Hou, Z., *Chem. Commun.*, 2012, vol. 48, p. 814.
57. Liu, F.-C., Chen, J.-H., Chen, S.-C., et al., *J. Organomet. Chem.*, 2005, vol. 690, p. 291.
58. Liu, F.-C., Chen, S.-C., Lee, G.-H., et al., *J. Organomet. Chem.*, 2007, vol. 692, p. 2375.
59. Liu, F.-C., Yang, C.-C., Chen, S.-C., et al., *Dalton Trans.*, 2008, no. 27, p. 3599.
60. Hesp, K.D., Kannemann, F.O., Rankin, M.A., et al., *Inorg. Chem.*, 2011, vol. 50, p. 2431.
61. Arnold, N., Mozo, S., Paul, U., et al., *Organometallics*, 2015, vol. 34, p. 5709.
62. Samigullin, K., Bolte, M., Lerner, H.-W., et al., *Organometallics*, 2014, vol. 33, p. 3564.
63. Murosaki, T., Kaneda, S., Maruhashi, R., et al., *Organometallics*, 2016, vol. 35, p. 3397.
64. Schmid, M., Guillaume, S.M., and Roesky, P.W., *J. Organomet. Chem.*, 2013, vol. 744, p. 68.
65. Saliu, K.O., Maunder, G., Ferguson, M.J., et al., *Inorg. Chim. Acta*, 2009, vol. 362, p. 4616.
66. Schmid, M., Guillaume, S.M., and Roesky, P.W., *Organometallics*, 2014, vol. 33, p. 5392.
67. Schmid, M., Ona-Burgos, P., and Guillaume, S.M., *Dalton Trans.*, 2015, vol. 44, p. 12338.
68. Chen, X., Lim, S., Plečnik, C.E., et al., *Inorg. Chem.*, 2005, vol. 44, p. 6052.
69. Tolpygin, A.O., Cherkasov, A.V., Fukin, G.K., et al., *Inorg. Chem.*, 2014, vol. 53, p. 1537.
70. Basalov, I.V., Rosca, S.C., Lyubov, D.M., et al., *Inorg. Chem.*, 2014, vol. 53, p. 1654.
71. Trifonov, A.A., Lyubov, D.M., Basalov, I.V., et al., *Russ. Chem. Bull. Int. Ed.*, 2018, vol. 67, p. 455.

Translated by E. Yablonskaya