

Selective Reduction of Carbon Dioxide to Bis(silyl)acetal Catalyzed by a PBP-Supported Nickel Complex†‡

Received 00th January 20xx,
Accepted 00th January 20xx

Pablo Ríos,^a Natalia Curado,^a Joaquín López-Serrano^{a*} and Amor Rodríguez^{a*}

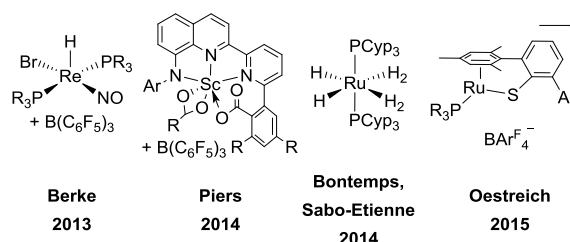
DOI: 10.1039/x0xx00000x

www.rsc.org/

Selective reduction of CO₂ to the formaldehyde level remains an important challenge and to date only a few catalysts have been developed for this reaction. Herein, we report an efficient catalyst that consists of a bis(phosphino)boryl nickel hydride complex in combination with B(C₆F₅)₃, for the highly selective hydrosilylation of CO₂ to bis(silyl)acetal derivatives.

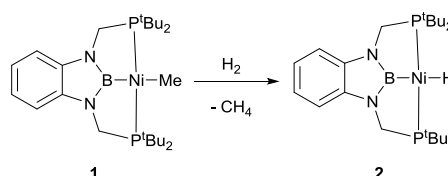
The use of carbon dioxide (CO₂) as a non-toxic, renewable and economical carbon source for the synthesis of liquid fuels and value added chemicals has attracted increasing attention over the last years.¹ Regarding the many catalytic transformations involving CO₂, those concerning its selective reduction represent an important challenge. In this sense, a substantial number of efficient transition metal catalysts for the conversion of carbon dioxide to formic acid, employing different reducing agents, have been reported.² Also, great efforts in the design of catalysts for the reduction of CO₂ to methanol^{3a,b} and methane^{3c-g} have been made. Nevertheless, catalysts that are selective enough for the controlled transformation of CO₂ to the formaldehyde level are very rare.⁴ Formaldehyde is an important industrial chemical with a world-wide production greater than 20 million tons per year. Currently, the large-scale synthesis of formaldehyde is based on the catalytic oxidation of methanol at high temperatures.⁵ In this sense, the use of CO₂ as a carbon source for the synthesis of CH₂O acquires great importance from both an industrial and an academic perspective. Recently, Bontemps and Sabo-Etienne reported the selective synthesis of formaldehyde by the borane reduction of CO₂ using ruthenium

and iron catalysts.^{4c,d} Likewise, Oestreich *et al.* have described the ruthenium-catalyzed reduction of CO₂ to bis(silyl)acetal or methyl silyl ether by adjusting the reaction temperature.^{4f} Finally, the groups of Berke and Piers applied the *frustrated Lewis pair (FLP)* concept to the selective hydrosilylation of CO₂, employing Rhenium and Scandium complexes in combination with B(C₆F₅)₃^{4a,b} (Scheme 1).



Scheme 1. Previously reported catalysts for the selective reduction of CO₂ to the formaldehyde level.

We have recently described the synthesis of a nickel methyl complex supported by a bis(phosphino)boryl (PBP) ligand [(PBP)NiMe] (**1**) that promotes the activation of H₂ through a cooperative metal-boryl mechanism, to form the hydride complex [(PBP)NiH] (**2**)^{6,7} (Scheme 2).



Scheme 2. Synthesis of **2**.

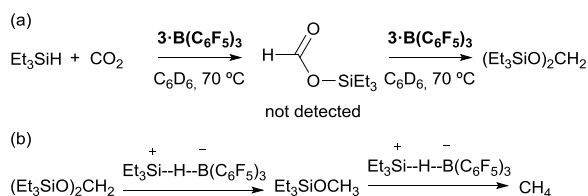
We envisioned that **2** could also serve as an efficient catalyst for the activation of carbon dioxide. In this regard, the insertion of CO₂ into a metal-hydrogen bond is assumed to be a key step in the catalytic conversion of CO₂ mediated by transition-metal complexes.⁸ This process is eased by the use of ligands that exert a strong *trans*-influence decreasing the Ni-H bond strength and increasing the nucleophilic character of the hydride group.⁹ Taking into account that boryl groups are

^a Instituto de Investigaciones Químicas-Departamento de Química Inorgánica. Centro de innovación en Química Avanzada (ORFEO-CINQA). Universidad de Sevilla-Consejo Superior de Investigaciones Científicas. Calle Américo Vesputio 49, 41092. Sevilla (Spain)

† This communication is dedicated to Professor José Gimeno on the occasion of his retirement.

‡ Electronic Supplementary Information (ESI) available: [details of any supplementary information available should be included here]. See DOI: 10.1039/x0xx00000x

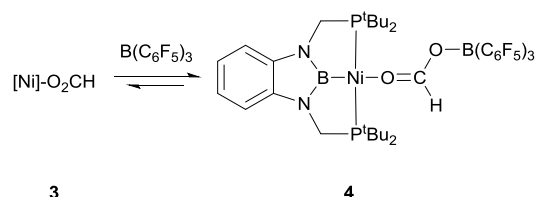
among the strongest *trans*-influence ligands known,¹⁰ we considered complex **2** an attractive candidate to study the activation of CO₂. Furthermore, from the economical point of view, the replacement of noble metals by earth abundant and cheaper ones is a desired goal in catalysis. In this communication, we describe a proficient nickel catalyst for the selective hydrosilation of carbon dioxide into bis(silyl)acetal derivatives with a catalytic activity comparable to the most effective catalysts reported so far.^{4b}



Scheme 3. a) Selective reduction of CO₂ to bis(silyl)acetal; b) Non observed over reduction products resulting from the hydrosilation catalyzed by B(C₆F₅)₃.

As we expected, treatment of **2** with CO₂ (1 bar, r.t.) gives the formate complex [(PBP)Ni(O₂CH)] (**3**) instantaneously. ¹H and ¹³C NMR spectra show resonances at 9.11 and 167.2 ppm respectively, that we assign to the formate group. The ³¹P and ¹¹B NMR spectra exhibit signals (δ_p 85.2; δ_B 37.5 ppm) at higher field than those observed for **2**. We remark that while we were immersed in this study, Lin and Peters reported the synthesis and characterization of **3**.⁷ In an effort to evaluate the suitability of **3** as a catalyst for hydrosilation of CO₂, we studied the stoichiometric reaction of **3** towards Et₃SiH. We observed that no reaction occurred at room temperature and heating of the solution at 40 °C provokes the decomposition of **3**.¹¹ At this point, based on previous work from Piers,^{4b} Berke^{4a} and others,^{3c,f,g} we ran this reaction in the presence of B(C₆F₅)₃. Thus, the addition of Et₃SiH (1 equiv) to a solution of **3** and B(C₆F₅)₃ (one equivalent relative to **3**) and CO₂ (4 bar) in C₆D₆ gives rise to the complete consumption of Et₃SiH and the selective formation of the bis(silyl)acetal derivative, after heating at 70 °C for 30 minutes (Scheme 3a). We also observed the formation of a new nickel complex generated by reaction of **3**, formed due to the presence of CO₂ in solution, with B(C₆F₅)₃. The nature of this new species will be discussed in detail below. The resonance due to the CH₂ group of (Et₃SiO)₂CH₂ appeared at 5.07 ppm in the ¹H NMR spectrum (See S7, Figure S8). Remarkably, no other over reduced products, formed by the hydrosilation of the bis(silyl)acetal catalyzed by free B(C₆F₅)₃, *i.e.* methyl silyl ether and methane (Piers-Rubinsztajn reaction), were detected during the reaction (Scheme 3b).¹² The high chemoselectivity observed justifies a detailed analysis of the reactions involved to elucidate the mechanism of this process. First, we decided to explore the reaction of **3** with B(C₆F₅)₃ to understand the precise nature of the catalyst. Thus, monitoring this reaction by NMR spectroscopy we observed the formation of a new complex **4** (Scheme 4). In the ¹H NMR spectrum the signal at 9.11 ppm, corresponding to the formate proton of **3**, disappeared and a new signal appeared at 8.45 ppm, as expected for a formato-

borate adduct. The ¹¹B spectra showed two new signals at 33 and -1.3 ppm that correspond to the boryl group and a



Scheme 4. Synthesis of complex **4**.

tetra-coordinated boron atom, respectively.^{3f,4b} We were able to obtain crystals of **4**, suitable for an X-ray diffraction analysis, by slow evaporation of a toluene solution (Figure 1). The solid-state structure of **4** revealed a slightly distorted square-planar geometry at nickel due to the geometric constraints imposed by the PBP pincer ligand (P-Ni-P angle = 158.61(2)°). The coordination of the formato-borate group is related to that reported by Piers^{3g,4b} in which a zwitterionic structure is adopted.¹³ Accordingly, the C25–O1 bond length (1.219 (2) Å) is significantly shorter than C25–O2 bond distance (1.283 (2) Å). Likewise, the Ni–O separation is slightly longer than that reported by Peters for [(PBP)Ni(O₂CH)].⁷ The B2–O2 bond length (1.552(2) Å) is similar to that observed in related zwitterionic species formed by CO₂ insertion into Frustrated Lewis pairs adducts.¹⁴ The structure of **4** was modeled by DFT analysis.¹⁵ The optimized structure was found to be a local energy minimum and an excellent agreement was obtained between calculated and experimental bond lengths and angles (See S7, table S2).

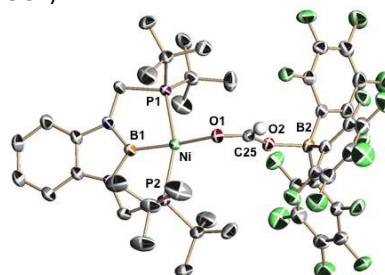


Figure 1. Ortep representation of **4**. Hydrogen atoms have been omitted for clarity (ellipsoids are drawn at 50% of probability). Selected bonds (Å) and angles (deg.): Ni–B = 1.903(2), Ni–O(1) = 1.978(1); O(1)–C(25) = 1.219(2); C(25)–O(2) = 1.283(2); P(1)–Ni–P(2) = 158.61(2); B(1)–Ni–O(1) = 171.34(6)

We explored the catalytic version of this reaction using 0.05 mol % of **4** (relative to silane) under 4 bar of CO₂ at 70 °C in C₆D₆. We observed transformation to bis(silyl)acetal after 21 hours, corresponding to a turnover number (TON) (based on mol of silane reacted per mol of catalyst) of 1200 and a turnover frequency (TOF) of 56 h⁻¹ (Table 1, entry 1). In order to investigate the scope of this reaction, several silanes were tested. Ph₂MeSiH leads to comparable selectivity to Et₃SiH though longer reaction times are required for similar conversions (Table 1, entry 4). On the contrary, a less bulky silane, such as PhMe₂SiH, reacts faster with CO₂ but small amounts of methyl silyl ether (8%) and methane (14%) are also

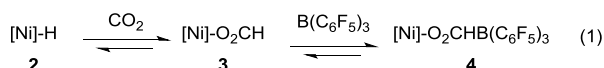
Table 1. Catalytic hydrosilylation of CO₂ to bis(silyl)acetal using **4**^[a]

Entry ^[a]	Silane	Catalyst [mol%]	Conv. ^[b] (%)	(R ₃ SiO) ₂ CH ₂	Time (h)	TON ^[c]	TOF (h ⁻¹)
1	Et ₃ SiH	0.05%	60	>99%	21.5	1200	55.8
2	Et ₃ SiH	0.1%	91	>99%	34	910	26.8
3	Et ₃ SiH	0.6%	86	>99%	15.5	143	9.2
4	Ph ₂ MeSiH	0.1%	62	>99%	37.5	620	16.5
5 ^[d]	Ph ₂ MeSiH	0.1%	41	>99%	22	410	18.6
6	Ph ₂ MeSiH	0.6%	82	>99%	7.5	137	18.3
7	PhMe ₂ SiH	0.6%	93	78%	3	121	40

[a] Reaction conditions: 70°C; C₆D₆. [b] Partial decomposition of the catalyst was observed after the conversions values indicated above. [c] Determined by ¹H NMR based on mol of silane consumed per mol of catalyst. [d] Neat silane was used.

formed together with the bis(silyl)acetal derivative (Table 1, entry 7). Interestingly, we observed that a high concentration of silane in the reaction solution increases considerably the reaction rate (See S8).¹⁶ It should be noted that, compared with the most effective catalyst reported so far, ours gives similar turnover numbers while turnover frequencies are significantly increased.^[4b]

On the other hand, it is well known the efficiency of B(C₆F₅)₃ as a catalyst for the hydrosilylation of bis(silyl)acetal derivatives to methyl silyl ethers and methane.¹² Recently, Turculet *et al.* have reported the catalytic reduction of CO₂ using platinum and palladium silyl pincer complexes in combination with B(C₆F₅)₃. At difference with our system, the presence of free borane in solution leads to the reduction of the bis(silyl)acetal derivative to methane and the corresponding bis(silyl)ether.^{3f} In this sense, the selectivity we observed suggests that no free borane is present or, at least, not in a significant amount during the catalysis.



Accordingly, in order to evaluate if the equilibrium shown in Equation 1 is operating under the catalytic conditions, a benzene solution of **4**-¹³CO₂ (prepared employing ¹³C-enriched CO₂) was heated in a NMR sealed tube during 4 hours at 70 °C. However, analysis by NMR spectroscopy (¹¹B, ¹⁹F and ¹³C) did not show resonances attributable to free B(C₆F₅)₃. Interestingly, when the NMR tube containing a solution of **4**-¹³CO₂ was charged with non-labeled CO₂ (1bar, 70°C, 22h), the incorporation of ¹²CO₂ was observed in a 12 % ratio (See S13, Figure S17), demonstrating that the equilibrium shown in Equation 1 takes place but is shifted to the right side, minimizing the free borane quantity in solution. These experimental observations agree well with the Gibbs energy difference of 15.2 Kcal mol⁻¹ between **4** (-27 Kcal mol⁻¹) and **3** + B(C₆F₅)₃ (-11.8 Kcal mol⁻¹) calculated by DFT analysis.^{15, 17}

To gain further insight into the mechanism about the formation of bis(silyl)acetal we monitored the catalytic reaction, by ¹H and ¹³C NMR spectroscopy, employing ¹³C-enriched CO₂ and Et₃SiH as reductant (See Figure 2). After 3h at 70°C, the ¹³C (fully coupled) experiment showed only a triplet signal at 85.5 ppm (J_{CH} = 161 Hz) that corresponds to

(Et₃SiO)₂CH₂ and the signal for free ¹³CO₂ (δ 124.9 ppm). After 8 h of heating, the signal of ¹³CO₂ decreased considerably in intensity and the major ¹³C-enriched species observable in the spectrum was (Et₃SiO)₂CH₂.¹⁸ Remarkably, the over reduced products that could be formed due to the presence of free borane in solution were not detected. At this point, B(C₆F₅)₃ (4 equivalents) was intentionally added to the solution resulting in the quantitative reduction of (Et₃SiO)₂CH₂ into methane and (Et₃Si)₂O, reinforcing the idea that **4** is the major species present in solution during the catalysis. Additionally, an isolated sample of (R₃SiO)₂CH₂ was reacted with B(C₆F₅)₃-activated silane yielding the quantitative formation of Et₃SiOSiEt₃ and methane (See S13, Figure S16).

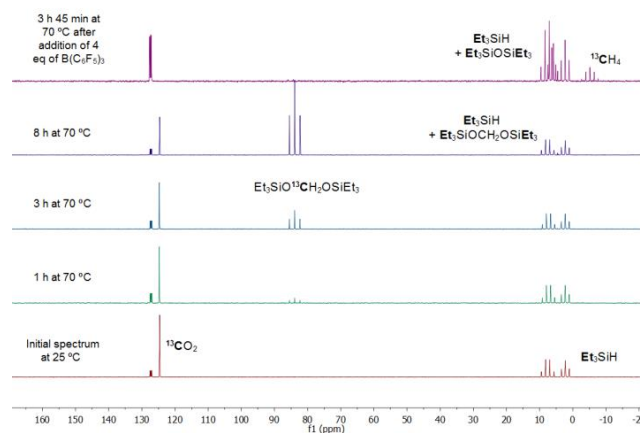
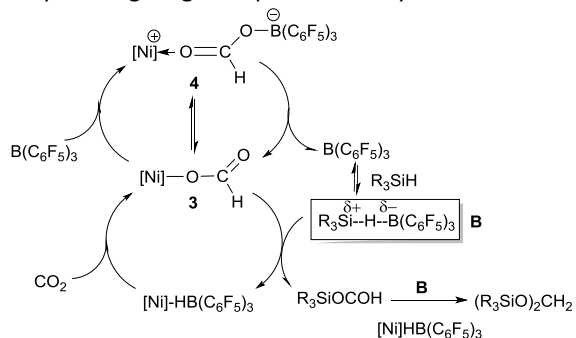


Figure 2. ¹³C NMR experiment of the reduction of ¹³CO₂ using Et₃SiH as reductant and **4** as catalyst (0.05 mol %)

From a mechanistic point of view, based on these findings and previous literature reports,^{4b} two different pathways may be proposed for the catalytic reduction of CO₂ using complex **4**: *i*) hydrosilylation (Si-H activation) mediated by **4** through a cooperative mechanism between the boryl moiety of the PBP ligand and the nickel center, similar to that reported by us for the activation of H₂;⁶ *ii*) reduction of the formate complex **3** by B(C₆F₅)₃-activated silane species (formed by dissociation of minor quantities of B(C₆F₅)₃ from **4**) to produce, initially, the silylester derivative (R₃SiOCOH). Then, reduction of R₃SiOCOH, mediated by a second equivalent of borane-activated silane (**B** in Scheme 5), gives the bis(silyl)acetal derivative. At this point,

the high selectivity observed implies that subsequent sequestration of $B(C_6F_5)_3$ by the metal complex is needed to avoid further reduction of $(R_3SiO)_2CH_2$, as postulated by Piers for his Scandium catalyst.^{4b} We propose that $B(C_6F_5)_3$ is trapped by the metal complex, either as the formaborate complex **4** or as the hydroborate complex $[Ni]HB(C_6F_5)_3$, preventing the formation of over reduced products. We are currently investigating both possibilities by DFT calculations.



Scheme 5. Proposed mechanism for the selective formation of bis(silyl)acetal.

In summary, an effective nickel catalyst for the selective reduction of CO_2 to bis(silyl)acetal derivatives has been developed. The highest TOFs (56 h^{-1} based on mol of silane) reported so far for this transformation have been achieved. Further mechanistic studies, that will allow a better understanding of the mechanism of this reaction and, in particular, the origin of the high selectivity for the formation of bis(silyl)acetals, are underway.

Financial support (FEDER contribution) from the MINECO (Projects CTQ2013-45011-P) and the Junta de Andalucía (Project FQM-2126) is gratefully acknowledged. Computational facilities of the Center of Supercomputing of Galicia (CESGA) are thankfully acknowledged.

Notes and references

- Q. Liu, R. Jackstell and M. Beller, *Nat. Commun.* 2015, **6**, 5933.
- For representative examples see: (a) R. Tanaka, M. Yamashita, and K. Nozaki, *J. Am. Chem. Soc.* 2009, **131**, 14168. (b) R. Langer, Y. Diskin-Posner, G. Leitner, L. J. W. Shimon, Y. Ben-David and D. Milstein, *Angew. Chem. Int. Ed.* 2011, **50**, 9948. (c) R. Lalrempuia, M. Iglesias, V. Polo, P. J. Sanz Miguel, F. J. Fernández-Álvarez, J. J. Pérez-Torrente and L. A. Oro, *Angew. Chem. Int. Ed.* 2012, **51**, 12824. (d) S. Wesselbaum, U. Hintermair and W. Leitner, *Angew. Chem. Int. Ed.* 2012, **51**, 8585. (e) C. Ziebart, C. Federsel, P. Anbarasan, R. Jackstell, W. Baumann, A. Spannenberg and M. Beller, *J. Am. Chem. Soc.* 2012, **134**, 20701. (f) J. F. Hull, Y. Himeda, W.-H. Wang, B. Hashiguchi, R. Periana, D. J. Szalda, J. T. Muckerman, and E. Fujita, *Nat. Chem.* 2012, **4**, 383. (g) M. S. Jeletic, M. T. Mock, A. M. Appel, and J. C. Linehan, *J. Am. Chem. Soc.* 2013, **135**, 11533. (h) S. Moret, P. J. Dyson and G. Laurenczy, *Nat. Commun.* 2014, **5**, 4017.
- (a) Y.-N. Li, R. Ma, L.-N. He and Z.-F. Diao, *Catal. Sci. Technol.*, 2014, **4**, 1498. (b) For the most efficient nickel catalysts see: S. Chakraborty, J. Zhang, J. A. Krause and H. Guan, *J. Am. Chem. Soc.* 2010, **132**, 8872. (c) T. Matsuo and H. Kawaguchi, *J. Am. Chem. Soc.* 2006, **128**, 12362. (d) M. Khandelwal and R. J. Wehmschulte, *Angew. Chem. Int. Ed.* 2012, **51**, 7323. (e) S. Park, D. Bézier and M. Brookhart, *J. Am. Chem. Soc.* 2012, **134**, 11404. (f) S. J. Mitton and L. Turculet, *Chem. Eur. J.*, 2012, **18**, 15258. (g) A. Berkefeld, W. E. Piers, M. Parvez, L. Castro, L. Maron and O. Eisenstein, *Chem. Sci.*, 2013, **4**, 2152.
- (a) Y. Jiang, O. Blacque, T. Fox and H. Berke, *J. Am. Chem. Soc.* 2013, **135**, 7751. (b) F.A. LeBlanc, W. E. Piers, and M. Parvez, *Angew. Chem. Int. Ed.* 2014, **53**, 789. (c) G. Jin, C. G. Werncke, Y. Escudie, S. Sabo-Etienne and S. Bontemps, *J. Am. Chem. Soc.* 2015, **137**, 9563. (d) S. Bontemps, L. Vendier and S. Sabo-Etienne, *J. Am. Chem. Soc.* 2014, **136**, 4419. (e) R. Declercq, G. Bouhadir, D. Bourissou, M.-A. Légaré, M.-A. Courtemanche, K.S. Nahi, N. Bouchard, F.-G. Fontaine and L. Maron, *ACS Catal.* 2015, **5**, 2513. (f) T. T. Metsänen and M. Oestreich, *Organometallics*, 2015, **34**, 543.
- G. Reuss, W. Disteldorf, A. O. Gamer and A. Hilt, *Formaldehyde*, Ullmann's Encyclopedia of Industrial Chemistry, Wiley-VCH, Weinheim, 2002.
- N. Curado, C. Maya, J. López-Serrano, and A. Rodríguez, *Chem. Commun.* 2014, **50**, 15718.
- When this work was under preparation Peters and Lin reported an alternative preparation of **2** and the insertion of carbon dioxide into the Ni-H bond to form the formate derivative **3**: J. Peters, and T.-P. Lin, *J. Am. Chem. Soc.* 2014, **136**, 13672.
- (a) T. G. Ostapowicz, M. Hölscher and W. Leitner, *Chem. Eur. J.* 2011, **17**, 10329. (b) H.-W. Suh, T. J. Schmeier, N. Hazari, R. A. Kemp and M. K. Takase, *Organometallics*, 2012, **31**, 8225.
- (a) R. Johansson and O. F. Wendt, *Organometallics*, 2007, **26**, 2426. (b) T. J. Schmeier, G. E. Dobreiner, R. H. Crabtree and N. Hazari, *J. Am. Chem. Soc.* 2011, **133**, 9274.
- J. Zhu, Z. Lin and T. B. Marder, *Inorg. Chem.* 2005, **44**, 9384.
- We observed the liberation of free PBP ligand and the presence of unidentified decomposition products.
- (a) It is well known that $B(C_6F_5)_3$ is able to abstract an hydride from a silane to form a borane-activated silane ($B(C_6F_5)_3\text{-HSiR}_3$) that mediates the hydrosilylation of $(Et_3SiO)_2CH_2$ to methane or methyl silyl ether. See references 3f and 3g. (b) D. J. Parks, J. M. Blackwell and W. E. Piers, *J. Org. Chem.* 2000, **65**, 3090. (c) S. Rubinsztajn and J. Cella, *Polym. Prep.*, 2004, **45**, 635.
- For species closely related to **4** see: (a) reference 3f. (b) H.-W. Suh, L. M. Guard and N. Hazari, *Chem. Sci.*, 2014, **5**, 3859.
- (a) A. Berkefeld, W. E. Piers and M. Parvez, *J. Am. Chem. Soc.* 2010, **132**, 10660. (b) I. Peuser, R. C. Neu, X. Zhao, M. Ulrich, B. Schirmer, J. A. Tannert, G. Kehr, R. Fröhlich, S. Grimme, G. Erker and D. W. Stephan, *Chem. Eur. J.*, 2011, **17**, 9640. (b) M. Harhausen, R. Fröhlich, G. Kehr and G. Erker, *Organometallics*, 2012, **31**, 2801. (c) D. W. Stephan, *J. Am. Chem. Soc.* 2015, **137**, 10018.
- The calculations were performed with the Gaussian 09 program: Gaussian 09, Revision D.01, Gaussian, Inc., Wallingford CT, 2010. The energies are free energies in benzene, relative to $2 + CO_2 + B(C_6F_5)_3$. The full Gaussian citation can be found in the supplementary information.
- (a) L. Zhang, J. Cheng and Z. Hou, *Chem. Commun.*, 2013, **49**, 4782. (b) E. A. Jaseer, M. N. Akhtar, M. Osman, A. Al-Shammari, H. B. Oladipo, K. Garcés, F. J. Fernández-Álvarez, S. Al-Khattaf and L. A. Oro, *Catal. Sci. Technol.* 2015, **5**, 274.
- In the Scandium system reported by Piers, in which a higher degree of $B(C_6F_5)_3$ dissociation is observed, a smaller ΔG value of 6.4 kcal mol^{-1} is obtained. See reference 3g.
- The resonance of the formate H atom of Et_3SiO_2CH at δ 7.85 ppm was detected in small amount at low concentrations of silane indicating the formation of the silyl ester derivative as intermediate. (See S9, Figure S10).