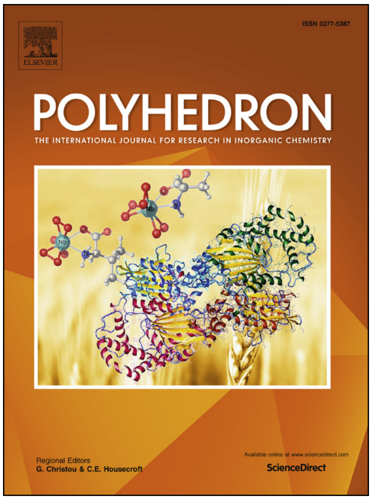


Synthesis of an Anionic Au(I) Hydroamination Precatalyst Supported by Charged Hydrido-Carboranyl Phosphine Ligands

Jack F. Kleinsasser, Sarah E. Lee, Christopher A. Lugo, Varun Tej, Scott G. McArthur, Vincent Lavallo

PII: S0277-5387(18)30579-5
DOI: https://doi.org/10.1016/j.poly.2018.09.027
Reference: POLY 13426

To appear in: *Polyhedron*

Received Date: 27 July 2018
Revised Date: 12 September 2018
Accepted Date: 14 September 2018

Please cite this article as: J.F. Kleinsasser, S.E. Lee, C.A. Lugo, V. Tej, S.G. McArthur, V. Lavallo, Synthesis of an Anionic Au(I) Hydroamination Precatalyst Supported by Charged Hydrido-Carboranyl Phosphine Ligands, *Polyhedron* (2018), doi: https://doi.org/10.1016/j.poly.2018.09.027

Synthesis of an Anionic Au(I) Hydroamination Precatalyst Supported by Charged Hydrido-Carboranyl Phosphine Ligands

Jack F. Kleinsasser, Sarah E. Lee, Christopher A. Lugo, Varun Tej, Scott G. McArthur, Vincent Lavallo

Department of Chemistry, University of California Riverside, Riverside CA 92521 USA

Abstract

Herein is reported the synthesis of an anionic gold complex bearing two charged hydrido carboranyl phosphine ligands. The compound is fully characterized by multinuclear NMR spectroscopy, high resolution mass spectrometry, as well as a single crystal X-ray diffraction study. In addition, we probe this compound's ability to catalyze the hydroamination of alkynes and compare its behavior to a related highly active catalyst supported by a perchlorinated carboranyl phosphine.

Keywords: Gold Catalysis; hydroamination; carborane anion; carborane ligand; electrostatic effects

1. Introduction

Neutral phosphine ligands are ubiquitous ancillary ligands in homogenous catalysis. Such species are typically appended with alkyl or aryl groups, to manipulate the steric environment and electronic properties of the metal center. Neutral *closo*-carborane clusters,[1-3] specifically $H_2C_2B_{10}H_{10}$ congeners, are alternative R-groups,[4, 5] which have been heavily investigated over the last 60 years. However, despite these efforts little progress has been made in developing competitive or superior catalysts, compared to classical systems supported by ligands with hydrocarbon R-groups. This fact is perhaps partially explained by the tendency of such clusters to undergo catalyst deactivation by cage degradation[4], B-H cyclometallation[6] reactions, or other degradation pathways.[7, 8] In contrast to neutral $H_2C_2B_{10}H_{10}$ clusters, their anionic analogue [$HCB_{11}H_{11}^{1-}$] and its derivatives,[9] are not susceptible to chemical cage degradation[10] and are more resistant to cyclometallation.[11]

Several years ago we began implementing a variety of ligands functionalized with such *closo*-carborane anions, including phosphine[11-16] and N-heterocyclic Carbenes.[17-20] So far we have found two examples of phosphine supported systems that display remarkable reactivity **1**[13] and catalytic activity **2**[15], respectively (Fig. 1). Compound **1** is a dianionic Pd(0) species that undergoes the oxidative addition of certain chloroarenes in less than 10 minutes at ambient temperature. No other isolable Pd(0) species has been reported to undergo such rapid oxidative addition reactions. The extreme reactivity of **1** was found both experimentally and computationally to be the result of electrostatic effects of coordinating two charged phosphine ligands to Pd(0). Electrostatic repulsion between the ligands, results in facile ligand dissociation of one phosphine, allowing immediate access to highly reactive mono phosphine ligated Pd(0). Compound **2** is a zwitterionic Au(I) species, which functions as a single component Au(I) catalyst that does not need an activator, such as Ag^+ or acid. This catalyst displays the highest activity yet reported for the hydroamination of amines with alkynes.[21, 22] Turn over numbers (TONs) of around 100,000 in a 24 hr period were observed for some substrates. The high activity of **2** is thought to result from the size of the ligand, which prevents double phosphine substitution, but more importantly the electrostatic stabilization of the Au(I) cation by field effects of the proximal carborane anion.

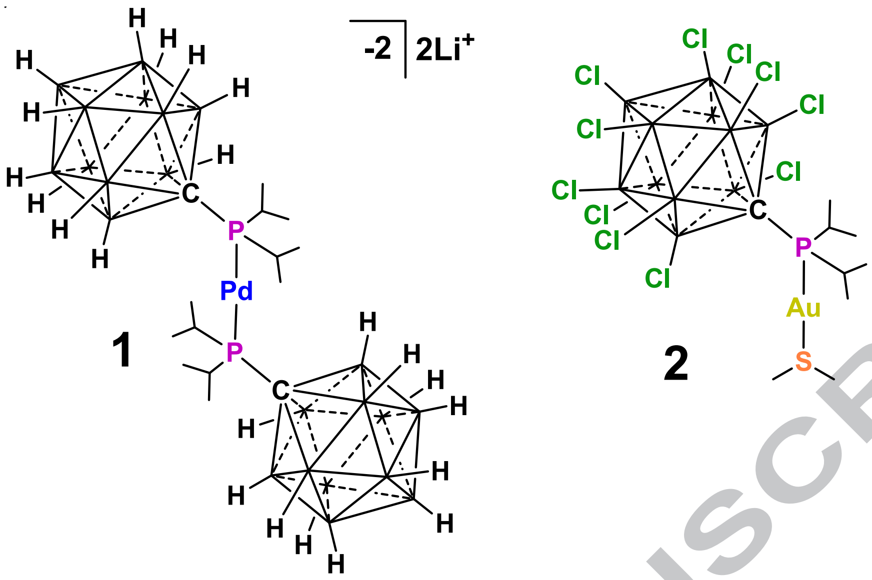


Figure 1. Dianionic Pd(0) complex **1** is the most active isolable compound for the oxidative addition of arylchlorides. Zwitterionic Au(I) complex **2** is the most active catalyst for the hydroamination of alkynes.

Here, we report our efforts to synthesize a linear monoanionic dicoordinate Au(I) complex analogous to **1**. The rational for this approach was that if facile ligand dissociation, similar to **1**, was observed when two charged phosphine ligands were attached to Au(I), we might be able to achieve an even more active system than **2**.

2. Materials and Methods

General Considerations: Unless otherwise stated, all manipulations were carried out using standard Schlenk or glovebox techniques (O_2, H_2O < 1ppm) under a dinitrogen or argon atmosphere. Solvents were dried on K or CaH_2 and distilled under argon before use. The ligand $Li(THF)_3[P(C_3H_7)_2CB_{11}H_{11}]$ **3** was prepared according to the literature procedure.[16] The amines were dried over CaH_2 and distilled before use. The alkynes were dried over molecular sieves and used without further purification. All other reagents were purchased from commercial vendors and used without further purification. Known catalytically produced imines from Table 1 were identified by comparison to their reported spectroscopic data for ^{1}H NMR and ^{13}C NMR (See Supplementary Information for characterization of products). NMR spectra were recorded at room temperature on Bruker Avance 300MHz, Bruker Avance 400MHz, or Bruker Avance 600MHz spectrometers. NMR chemical shifts are reported in parts per million (ppm). ^{1}H NMR and ^{13}C NMR chemical shifts were referenced to residual protio solvent. ^{11}B NMR chemical shifts were externally referenced to BF_3OEt_2. ^{31}P NMR chemical shifts were externally referenced to 80% H_3PO_4 in H_2O. The mass spectrometry data was collected on an Agilent LCTOF Multimode-ESI/APCI with direct injection.

2.1 Synthesis of ***4*** $Au((P(C_3H_7)_2CB_{11}H_{11})_2)Li$

In a vial equipped with a stir bar, **3** (757 mg, 1.57 mmol) and $ClAuSMe_2$ (462 mg, 1.57 mmol) were added and subsequently dissolved in 10 mL of methylene chloride. The mixture was stirred and a white precipitate rapidly formed. After one hour the mixture was filtered through a glass pipette plugged with glass microfiber to remove LiCl. The solvent was removed under vacuum and remaining solid was washed with pentane. The compound was dried under vacuum overnight to afford the purified product (yield = 701.0 mg, 1.35 mmol, 86.1%). Crystals suitable for X-ray diffraction were obtained by layering a CH_2Cl_2 solution of **4** with pentane. m.p. = 110°C. NMR ^{1}H (300 MHz, CD_2Cl_2, 25°C): δ = 3.79 (m, 12H, THF), 2.53 (d-sep, J^3(H,H) = 7.2 Hz, J^2(H,P) = 4.0 Hz, 1H, CH), 1.95 (m, 12H, THF), 1.44 (m, 6H, CH_3), 1.35 (m, 6H, CH_3); ^{1}H[^{11}B] (300 MHz, CD_2Cl_2, 25°C): 2.13 (br-s, 5H, BH), 1.96 (br-s, 1H, BH), 1.72 (br-s, 5H, BH); ^{31}P[^{1}H] (162 MHz, THF-d_8, 25°C): 83.6; ^{13}C[^{1}H] NMR (101 MHz, CD_2Cl_2, 25°C): 69.0, 28.8, 25.8, 22.6, 19.2; ^{11}B (96 MHz, CD_2Cl_2, 25°C): -2.9 (d, 1B, J^1(B,H) = 120 Hz), −11.7(d, 5B, J^1(B,H) = 120 Hz), −12.9(d, 5B, J^1(B,H) = 120 Hz); HRMS: (Multimode-ESI/APCI) [M]- m/z calc'd for $H_{34}B_{11}C_{11}PAu$: 715.5239; found: 715.5432.

2.2 General procedure for catalytic experiments

A standard solution of **4** was prepared in dry CH_2Cl_2 and the desired amount of catalyst was immediately transferred via micropipette to screw capped (PTFE) vials. The CH_2Cl_2 solution was removed by placing under vacuum for 10 minutes and a stir bar was subsequently added. The amines and alkynes were then transferred via micropipette (or added directly if solid) to the screw capped vials which were then sealed and heated to the indicated temperature and stirred for the allotted times (**Table 1**, Results and Discussion). Yields were calculated by integration of the ^{1}H NMR, via direct comparison of the imine formed to the amine consumed (no side reactions were observed). The validity of this approach was confirmed by obtaining isolated yields of several compounds. The products were isolated via column chromatography or by crystallization at -25˚C in hexanes.

3. Results and Discussion

Given our success at preparing the diphosphine substituted Pd(0) species **1[13]** we imagined it should certainly be possible to form a similar compound with Au(I) as gold is a larger atom. Thus, we reacted two equivalents of ligand **3** with ClAu(SMe_2) in methylene chloride solvent, and a white precipitate of LiCl immediately formed. After filtration and concentration of the supernate the residue was analyzed by mass spectrometry (negative-ion mode), which showed a molecular ion peak corresponding to the formation of a gold complex bearing two carboranyl phosphines. Analysis of the ^{1}H NMR spectrum of the residue in CD_2Cl_2 reveals the existence of THF, which

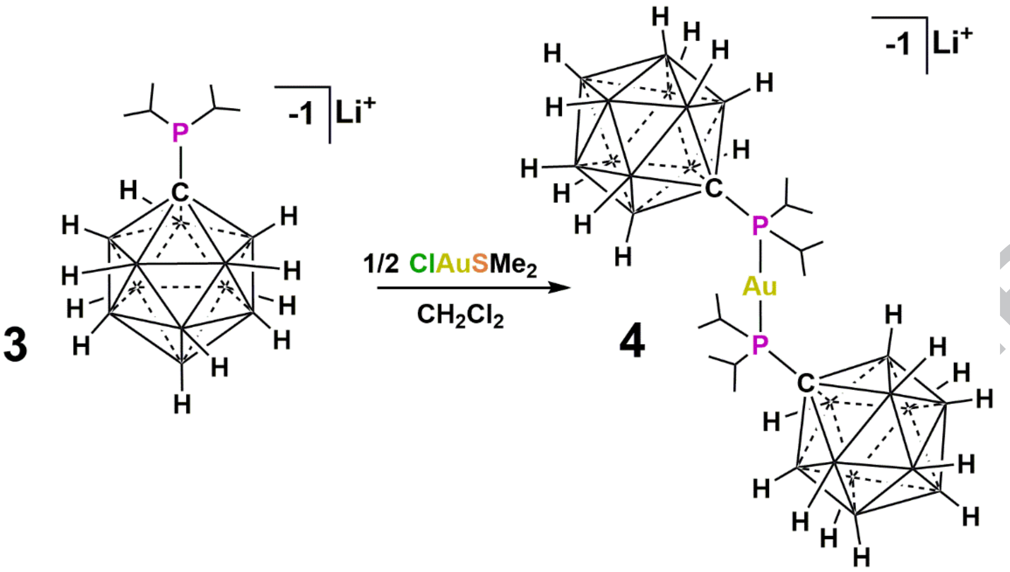


Figure 2. Synthesis of anionic Au(I) complex **4**.

suggests the presence of a lithium cation coordinated by THF, consistent with the formation the anionic complex **4**. Integration of the THF peaks shows that there are three THF molecules coordinated to the Li cation. Additionally, we see the signature isopropyl multiplets at 2.53 ppm and 1.44 through 1.35 ppm, indicating the presence of the carboranyl phosphine. One resonance is present in the ^{31}P NMR at 81.2 ppm, indicating a single phosphorus product. Analyzing the ^{11}B NMR presents three peaks at -2.8, -11.7, and -12.9 ppm, respectively, in a 1:5:5 ratio showing that the local C_5v symmetry of the cluster is preserved.

3.1 Crystal Structure

A single crystal X-ray diffraction study unambiguously confirmed the structure of **4**. In the solid-state, **4** displays the expected perfectly linear geometry (P-Au-P angle = 180˚) of a symmetrical dicordinate Au(I) complex, as well as a single lithium counter cation coordinated by THF (Figure 3). The P-Au-P bond lengths are 2.3079(5) and 2.3099(2) Å, close to both the reported P-Au bond length for the neutral ortho-dicarba-closo-decaborane-substituted phosphine–AuCl complex (2.232(3) Å)[23] and the anionic carborane substituted phosphine-AuCl in **2** (2.2477(12) Å).[15]

The closest B-H distance to the Au(I) center is 3.001(5) Å, which is outside of the range for covalent Au-H interactions, demonstrating that the carborane anion substituent does not interact strongly with the cationic Au center.

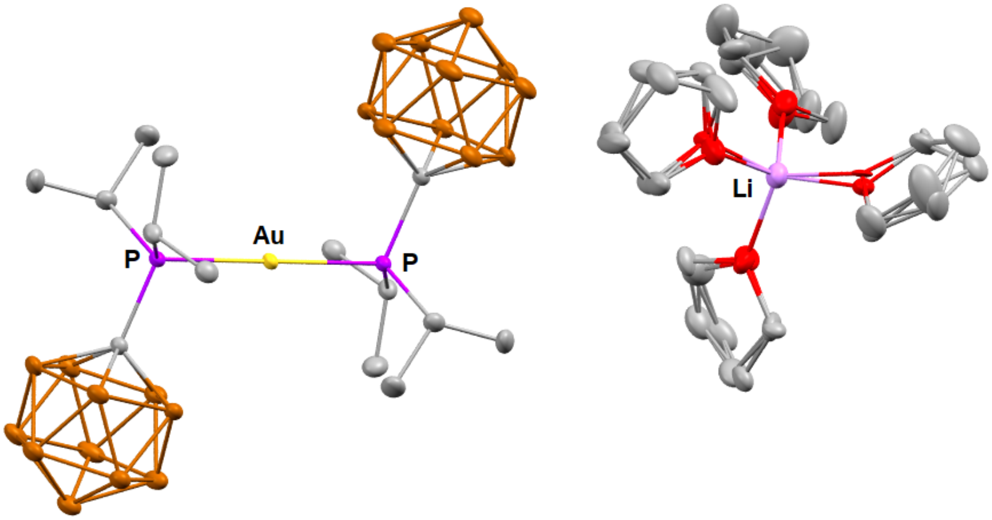
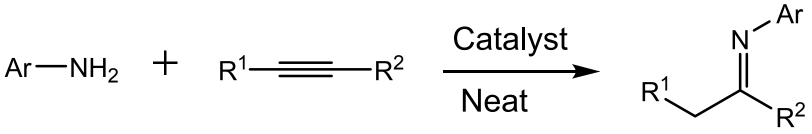


Figure 3. Solid-state structure of **4**. Thermal ellipsoids drawn at the 50% probability level and hydrogen atoms omitted for clarity. Note: THF molecules coordinated to Li^+ disordered over two positions. Color code: grey = carbon, brown = boron, violet = phosphorus, yellow = gold, red = oxygen, pink = lithium.

3.2 *Catalytic Activity*

We next investigated the catalytic activity of complex **4** towards the hydroamination of alkynes with primary amines (Table 1) and compared its behavior to the previously reported catalyst **2**[15] (Figure 1). Unlike **2,** complex **4** did not produce any hydroamination products with any of the chosen substrates at ambient temperature, run under neat conditions. In fact, reasonable rates of conversion were not observed until 80 °C. Our initial test substrates, aniline and phenylacetylene, were reacted with a 1.0% catalyst loading, producing the corresponding imine in 90% yield (TON = 90) after 24 hours (Table 1, entry 1). Dropping the catalyst loading to 0.5 and

Table 1. Hydroamination of alkynes with primary amines in the presence of catalyst 4.



Entry	Ar	R1	R2	Catalyst Loading [%]	T[^{o}C]	Yield [%][a][b]	TON 24 hr
1	Ph	H	Ph	1.0	80	90	90
2	Ph	H	Ph	0.5	80	86	172
3	Ph	H	Ph	0.1	80	77 (74)	765
4	Mes	H	Ph	0.1	80	71	710
5	Dipp	H	Ph	1.0	80	80 (74)	80
6	Ph	H	4-FC_6H_4	1.0	80	90 (86)	90
7	Mes	H	4-FC_6H_4	1.0	80	90	90
8	Dipp	H	4-FC_6H_4	1.0	80	87 (83)	85
9	Ph	H	4-$MeOC_6H_6$	0.1	80	92	920
10	Mes	H	4-$MeOC_6H_6$	0.1	80	95 (92)	950
11	Dipp	H	4-$MeOC_6H_6$	0.1	80	78	780
12	Ph	H	*n*-C_4H_9	1.0	80	65	65
13	Mes	H	*n*-C_4H_9	1.0	80	55	55
14	Dipp	H	*n*-C_4H_9	1.0	80	50	50

[a] The yield was determined by NMR spectroscopy by the direct integration of the peak for the amine starting material with respect to the peak for the imine product. [b] The yield of the isolated product is given in parentheses. Dipp = 2,6-diisopropylphenyl, Mes = mesityl (2,4,6,-trimethylphenyl).

0.1 mol% respectively, resulted in reasonable but lower yields (86%: TON = 177; 77%: TON = 765; respectively) (Table 1, entries 2 and 3). Comparatively, **2** catalyzes this reaction with a 0.1 mol% loading at ambient temperature in one hour to produce the product in > 95% yield (TON >950). Furthermore, catalyst **2** achieves an identical yield even with 0.01 mol% loading but at only slightly elevated temperatures (50 °C). Complex **4** shows similar performance with the larger mesityl amine (71%; TON = 710), but the very sterically demanding 2,6-diisoppropylamine required the utilization of higher catalyst loading (1 mol%) to a achieve any appreciable conversion (Table 1, entries 4 and 5, respectively). On the other hand, complex **2** catalyzes these reactions at 50 °C with 0.001% loading to achieve maximum turnovers of 67,000 and 85,000, respectively. In contrast to **4**, catalyst **2** displays a clear trend in improved yields with bulkier amines for all substrates tested, which was rationalized by sterically related amine substrate and imine product inhibition. Catalyst **4** mediated the hydroamination of the electron poor alkyne *para*-fluorophenylacetylene with all three sterically differentiated amines providing the imine products in 85-90% yields (table 1, entries 6-8). However, appreciable conversions were not observed below 1.0 mol% catalyst loading. In contrast, the zwitterionic catalyst **2** mediates these reactions at 50 °C with 0.001 mol% loading and achieves TONs between 54,000-92,000. Complex **4** is highly active for the hydroamination of the electron rich alkyne, *para*-methoxyphenylacetylene, producing the imine products in 78-92% yield at 0.1 mol% loading (Table 1, entries 9-11). However, complex **2** is again far more active for these reactions, achieving 90,000-95,000 turnovers for the same amines at 0.001 mol% loading. Complex **4** was less active for the hydroamination of the alkyl substituted alkyne, 1-hexyne, affording the ensuing imines in 50-65% yields at 1.0 mol% loading (Table1, entries 12-14). Comparatively, catalyst **2** is an order of magnitude more active for the same substrates at the same temperature. Additionally, we attempted to react an internal alkyne, biphenylacetylene, but the resulting TONs were less than 5% after 24 hours which were not included in the table. Catalyst **2** on the other hand, could achieve yields between 67 and 89%, depending on the amine, at 80 °C with 0.1 mol% loading.

The difference in reactivity between **2** and **4** can likely be explained, in part, by the fact that in contrast to our initial hypothesis, repulsive electrostatic effects in this system are not strong enough to induce facile phosphine dissociation, as they are in the analogous Pd(0) species. Since Au(I) is formally positively charged, in contrast to Pd(0), some of the electrostatic repulsion between the anionic carborane substituents is negated, rendering phosphine ligand dissociation less favorable. Indeed, we monitored by ^{31}P NMR the hydroamination reaction of aniline and phenylacetylene at both 1.0% and 0.1% catalyst loading and saw no change in the ^{31}P at ambient temperature, confirming that the phosphines of **4** are not labile without external heating. In addition, at completion of the heated reactions with **4** we visually notice the formation of colored Au nanoparticles and metal plating on the reaction vessels, whereas with complex **2** we see no such visual cues of decomposition. This observation is in line with the far greater chemical stability of the perchlorinated carborane present in **2**. Lastly, although not quantified but empirically noted based on the difference of C-H acidities of the [$HCB_{11}H_{11}^{1-}$] and [$HCB_{11}Cl_{11}^{1-}$] anions,[24] the perchlorinated carboranyl substituent should be a far stronger electron withdrawing group compared to its hydric congener, thus rendering this phosphine a weaker donor and the Au a stronger π-acid towards alkynes.

4. Conclusion

An anionic gold complex **4** bearing two charged hydrido carboranyl phosphine ligands is reported and fully characterized. In contrast to the previously reported mono-phosphine ligated zwitterionic Au(I) species **2**, supported by a phosphine with a perchlorinated carborane anion substituent, **4** is much less catalytically active for the hydroamination of alkynes. The difference in reactivity can likely be explained by the overall superior stability and π-acidity of **2**, and also the reluctance of one of the phosphines in **4** to dissociate. Given these results, subsequent investigations into such systems will focus on monophosphine ligated zwitterionic species with enhanced π-acidity.

Acknowledgments

We are grateful to the National Science Foundation of the USA for funding this work (Grant CHE-1455348). We thank Fook S. Tham (U.C.R.) for X-ray crystallographic analysis.

Appendix A

Supplementary data CCDC <1850911> contains the supplementary crystallographic data for <**4**>. These data can be obtained free of charge via http://www.ccdc.cam.ac.uk/conts/retrieving.html, or from the Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: (+44) 1223-336-033; or e-mail: deposit@ccdc.cam.ac.uk.

References

[1] R.N. Grimes, Carboranes in the chemist's toolbox, Daltons Trans. 44(13) (2015) 5939-5956.
[2] A.M. Spokoyny, New ligand platforms featuring boron-rich clusters as organomimetic substituents, Pure Appl. Chem. 85(5) (2013) 903-919.
[3] M. Scholz, E. Hey-Hawkins, Carbaboranes as Pharmacophores: Properties, Synthesis, and Application Strategies, Chem. Rev. 111(11) (2011) 7035-7062.
[4] A.R. Popescu, F. Teixidor, C. Viñas, Metal promoted charge and hapticities of phosphines: The uniqueness of carboranylphosphines, Coord. Chem. Rev. 269(0) (2014) 54-84.
[5] D. Olid, R. Núñez, C. Viñas, F. Teixidor, Methods to produce B-C, B-P, B-N and B-S bonds in boron clusters, Chem. Soc. Rev. 42(8) (2013) 3318-3336.
[6] B.J. Eleazer, D.V. Peryshkov, Coordination Chemistry of Carborane Clusters: Metal-Boron Bonds in Carborane, Carboranyl, and Carboryne Complexes, Comments Inorg. Chem. (2018) 1-30.
[7] C. Viñas, R. Núñez, F. Teixidor, R. Sillanpää, R. Kivekäs, Formation of B−P Bonds through the Reaction of nido-Monophosphinocarboranes with Palladium(II) Complexes. The First Example of a Chelating R2P−C−B−PR2 Diphosphine, Organometallics 18(23) (1999) 4712-4717.
[8] F. Teixidor, J. Casabo, A.M. Romerosa, C. Vinas, J. Rius, C. Miravitlles, Simultaneous conversion of Pd-PPh3 and B-H to B-PPh2 under exceedingly mild conditions. Crystal and molecular structure of PdPPh3Cl{7-SMe-8-Me-11-PPh2-7,8-C2B9H10}, J. Am. Chem. Soc. 113(26) (1991) 9895-9896.
[9] C. Douvris, J. Michl, Update 1 of: Chemistry of the Carba-closo-dodecaborate(−) Anion, CB11H12−, Chem. Rev. 113(10) (2013) PR179-PR233.
[10] C.A. Reed, H+, CH3+, and R3Si+ Carborane Reagents: When Triflates Fail, Acc. Chem. Res. 43(1) (2009) 121-128.
[11] J. Estrada, S.E. Lee, S.G. McArthur, A. El-Hellani, F.S. Tham, V. Lavallo, Resisting B–H oxidative addition: The divergent reactivity of the o-carborane and carba-closo-dodecaborate ligand substituents, J. Organomet. Chem. (0).
[12] J. Estrada, C.A. Lugo, S.G. McArthur, V. Lavallo, Inductive effects of 10 and 12-vertex closo-carborane anions: cluster size and charge make a difference, Chem. Commun. 52(9) (2016) 1824-1826.
[13] A.L. Chan, J. Estrada, C.E. Kefalidis, V. Lavallo, Changing the Charge: Electrostatic Effects in Pd-Catalyzed Cross-Coupling, Organometallics 35(19) (2016) 3257-3260.
[14] J. Estrada, D.H. Woen, F.S. Tham, G.M. Miyake, V. Lavallo, Synthesis and Reactivity of a Zwitterionic Palladium Allyl Complex Supported by a Perchlorinated Carboranyl Phosphine, Inorg. Chem. 54(11) (2015) 5142-5144.

[15] V. Lavallo, J.H. Wright, F.S. Tham, S. Quinlivan, Perhalogenated Carba-closo-dodecaborate Anions as Ligand Substituents: Applications in Gold Catalysis, Angew. Chem. Int. Ed. 52(11) (2013) 3172-3176.

[16] A. El-Hellani, C.E. Kefalidis, F.S. Tham, L. Maron, V. Lavallo, Structure and Bonding of a Zwitterionic Iridium Complex Supported by a Phosphine with the Parent Carba-closo-dodecaborate CB11H11– Ligand Substituent, Organometallics 32 (2013) 6887-6890.

[17] E. Jess, L. Vincent, Fusing Dicarbollide Ions with N-Heterocyclic Carbenes, Angew. Chem. Int. Ed. 56(33) (2017) 9906-9909.

[18] S.P. Fisher, A. El-Hellani, F.S. Tham, V. Lavallo, Anionic and zwitterionic carboranyl N-heterocyclic carbene Au(i) complexes, Daltons Trans. 45(24) (2016) 9762-9765.

[19] M.J. Asay, S.P. Fisher, S.E. Lee, F.S. Tham, D. Borchardt, V. Lavallo, Synthesis of unsymmetrical N-carboranyl NHCs: directing effect of the carborane anion, Chem. Commun. 51 (2015) 5359-5362.

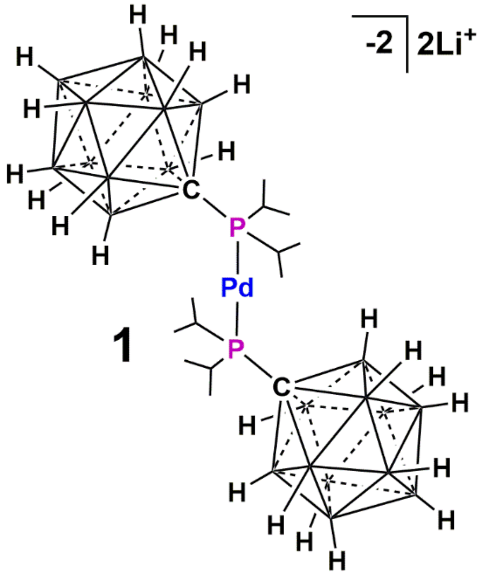
[20] A. El-Hellani, V. Lavallo, Fusing N-Heterocyclic Carbenes with Carborane Anions, Angew. Chem. Int. Ed. 53(17) (2014) 4489-4493.

[21] B.A. Sergey, P.B. Irina, Gold as a catalyst. Part I. Nucleophilic addition to the triple bond, Russian Chemical Reviews 86(8) (2017) 689.

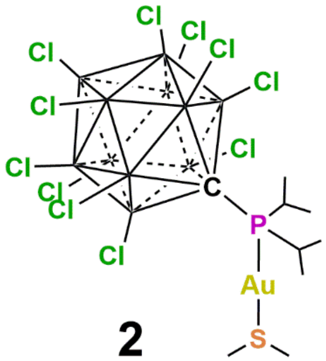
[22] L. Huang, M. Arndt, K. Gooßen, H. Heydt, L.J. Gooßen, Late Transition Metal-Catalyzed Hydroamination and Hydroamidation, Chem. Rev. 115(7) (2015) 2596-2697.

[23] M.A. McWhannell, G.M. Rosair, A.J. Welch, 1-[Chloro(diphenylphosphino)gold(I)-P]-2-phenyl-1,2-dicarba-closo-dodecaborane(12), Acta Crystallographica Section C 54(1) (1998) 13-15.

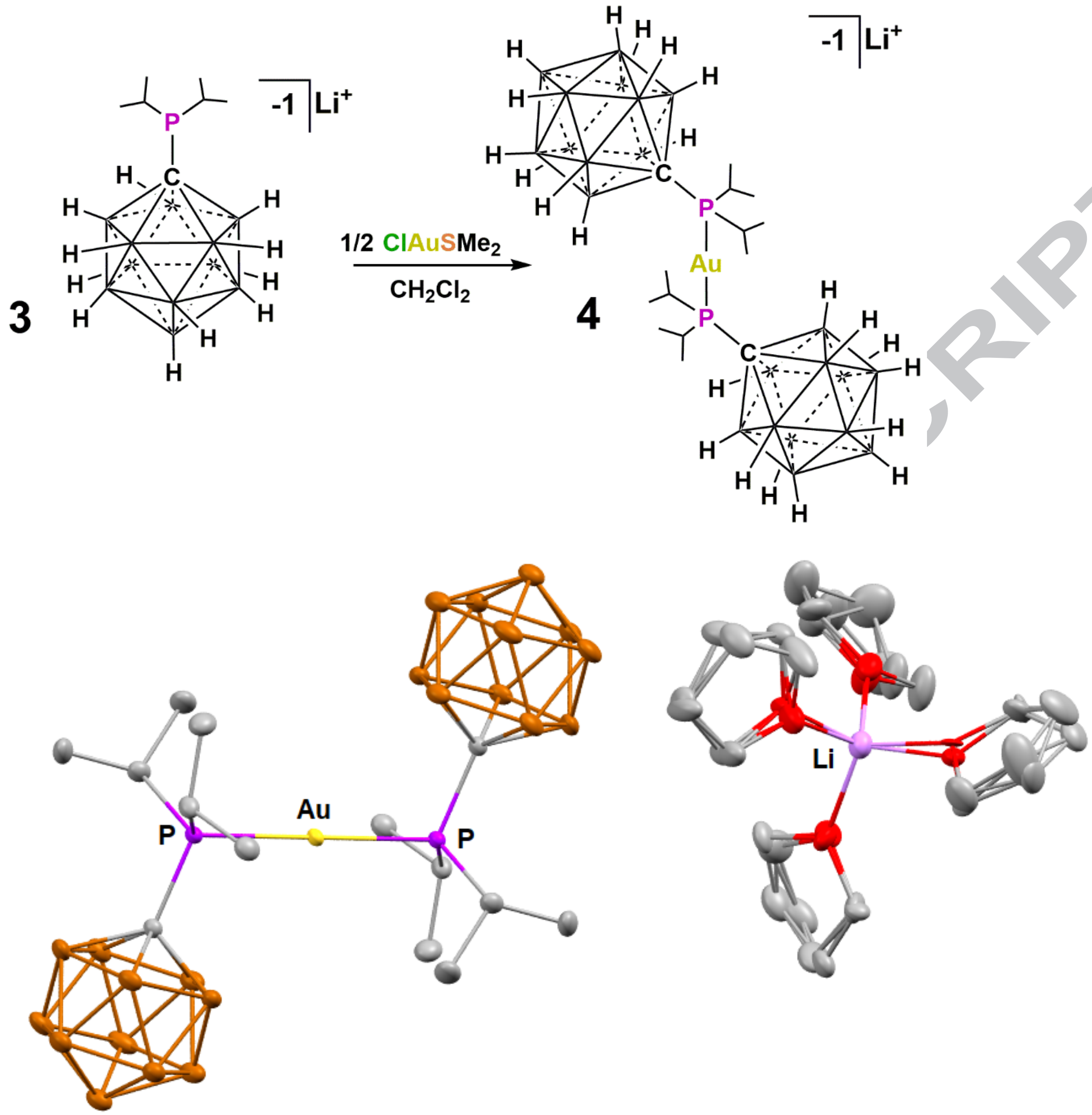
[24] R. Ramírez-Contreras, O.V. Ozerov, Convenient C-alkylation of the [HCB11Cl11]− carborane anion, Daltons Trans. 41(26) (2012) 7842-7844.



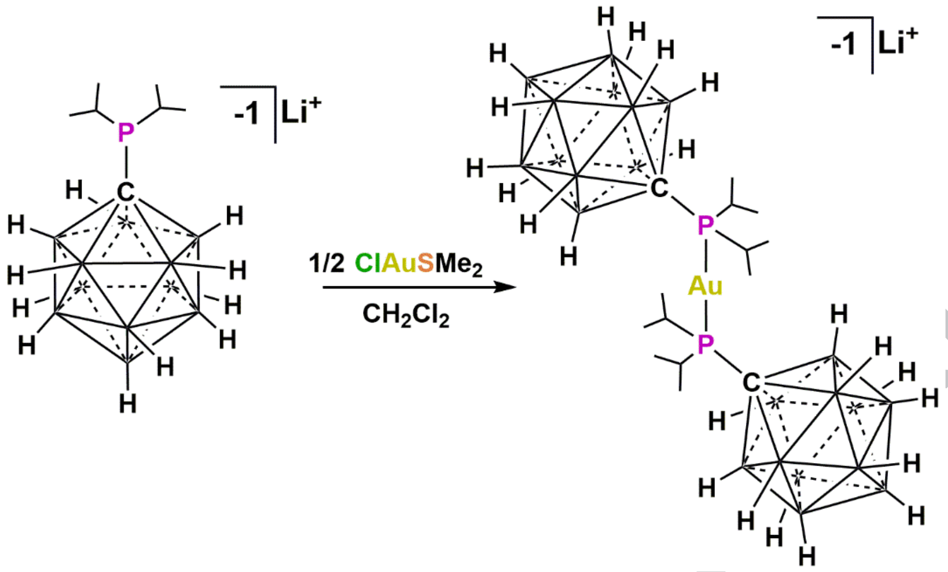
1



2

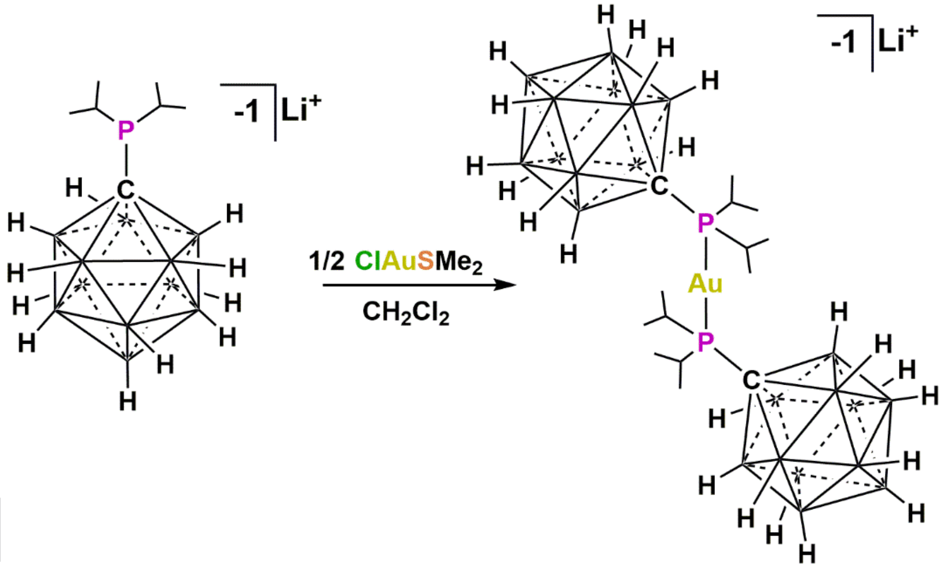


Figure



Synopsis: An anionic Au(I) complex supported by two charged carboranyl phosphines is reported. Its catalytic activity for the hydroamination of alkynes is investigated and compared to the most active known system.

Figure



Synopsis: An anionic Au(I) complex supported by two charged carboranyl phosphines is reported. Its catalytic activity for the hydroamination of alkynes is investigated and compared to the most active known system.