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A stable Cerberus tris(*malo*NHC) and its coinage metal complexes

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The first trisanionic Cerberus-type *malo*NHC has been generated and coordinated to two different coinage metals (Au(I) and Ag(I)). The resulting triszwitterionic metal complexes have been characterized by NMR spectroscopy, elemental analysis, and X-ray crystallography. The molecular structures of the new metal complexes reveal an average Au···Au and Ag···Ag separation of 20.89 and 21.03 Å respectively, the longest distances reported to date for any related Cerberus-type NHCs.

Since their isolation nearly three decades ago,[1] *N*-heterocyclic carbenes (NHCs) have attracted extensive interest not only in the area of catalysis, but also in medicinal chemistry, polymer chemistry and material science among others.[2] Therefore, a vast repertoire of mono- and poly-NHCs customized for specific applications is now available in the literature. Rigid multitopic NHCs featuring geometrically isolated carbene moieties are vital for the advancement of NHC-based multifunctional materials. While still underdeveloped, Janus- and Cerberus-type bridging NHCs have found in the recent years great utility as building blocks for robust multimetallic catalysts and versatile supramolecular structures and macromolecules with useful electronic and structurally dynamic properties.[3-5] Among these type of substrates, compounds **1**-**4** in Figure 1 are the only Cerberus-type trisNHC known to date. While **1**[5a-c, 5f] and **2**[5d] display three NHC moieties connected by a π-delocalized polyaromatic system (triphenylene and hexaazatriphenylene, respectively), carbene **3**[5g] with a triptycene core and carbene **4**[5e] with a tribenzotriquinacene core lack the extended π-conjugated bridging system. These four carbenes have been successfully incorporated in a variety of trimetallic complexes, organometallic polymers and supramolecular structures with interesting catalytic properties.[5]

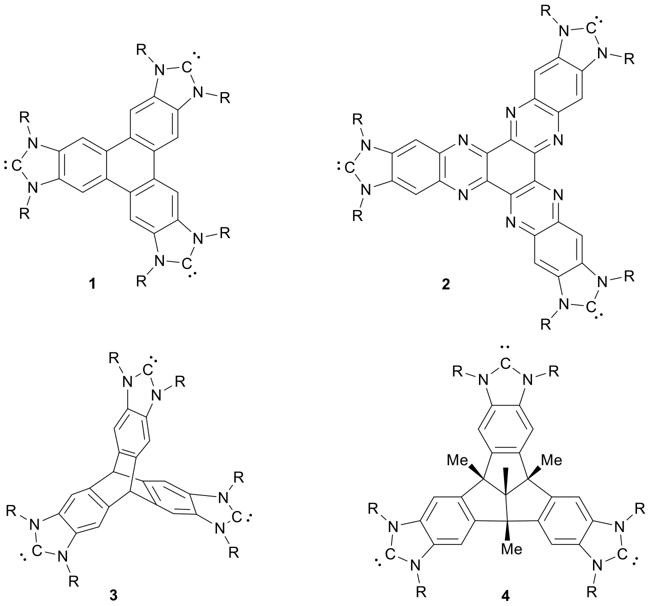

Fig. 1 Examples of known neutral Cerberus-type NHC

However, while several examples of such multitopic bridging neutral NHCs have been introduced in the literature to date, limited progress was registered towards the development of their anionic counterparts. The only examples of dianionic Janus-type NHCs, carbenes **5**[6] and **6**,[7] were recently reported by our group (Figure 2). These rigid rod-like systems are composed of two linearly opposed *malo*NHCs connected by either a rigid phenylene or a terphenylene fragment. While carbene **5** can establish a separation between the two carbene centers of 11.5 Å, bisNHC **6** displays a significant larger separation of 20 Å, the longest among all previously reported bridging biscarbenes. Digold and disilver complexes of **6** exhibit a remarkably long metal-to-metal through space distance of

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24.2 Å, the longest distance reported so far for a Janus-type NHC ligand.

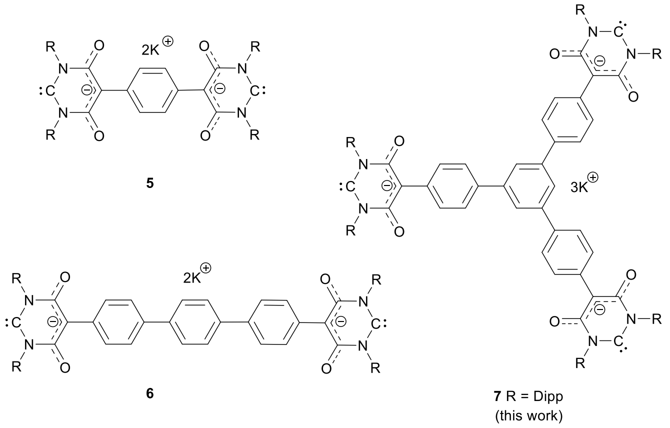
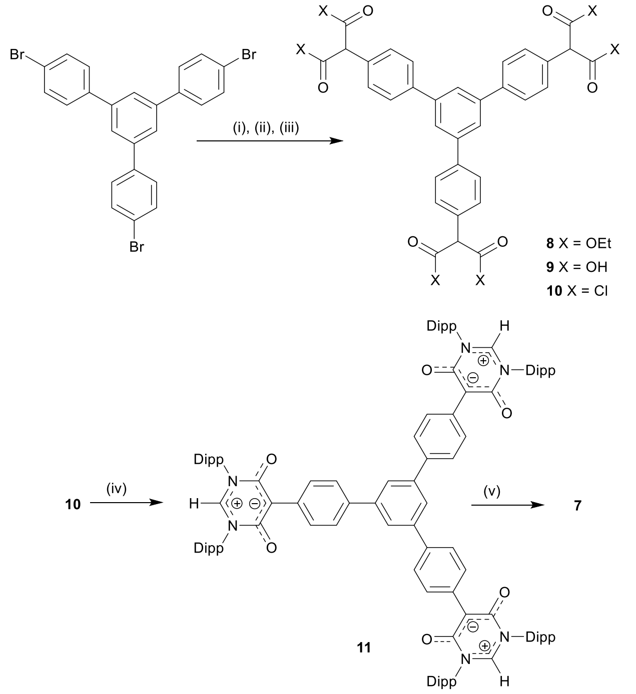


Fig. 2 Examples of anionic multitopic NHCs

To expand on this novel family of ligands, herein we report the synthesis and characterization of the first trisanionic Cerberus-type NHC, carbene **7**. This carbene exhibits three equilaterally opposed NHC moieties connected by the rigid 1,3,5-triphenylbenzene core. Due to the presence of the three remote malonate moieties, this carbene has a net (-3) overall charge. By complexation to different metals, this new NHC is prone to displace existing anionic ligands and lead to neutral triszwitterionic metal complexes,[6-8] novel architectures that are currently not accessible from its neutral trisNHC couterparts, carbenes **1**-**4**. Moreover, *malo*NHCs are among the most overall electron-donating cyclic diaminocarbenes[8c, 8f, 8h, 9] and their electronic properties can be easily tuned post-complexation by trapping the *malo*-moiety with an electrophile.[8c, 8e, 8f] Due to its unique electronic properties and rigid architecture, we envision using carbene **7** as a versatile building block for the development of a multitude of trimetallic complexes, along with supramolecular structures and organometallic polymers. The coordination of **7** to two different coinage metals (Au(I) and silver(I)) is detailed herein.



Scheme 1. Synthesis of trisNHC **7**. Conditions: (i) diethyl malonate, Pd(dba)$_2$, *t*Bu$_2$PNp, NaH, toluene, 70 °C; (ii) 1. 12.5 eq. KOH, in 50% ethanol/H$_2$O; 2. HCl; (iii) (COCl)$_2$, DMF (cat.), dichloromethane ; (iv) *N,N'*-bis(2,6-di-isopropylphenyl) formamidine, Et$_3$N, dichloromethane, 0 °C; (v) KHMDS in DMSO-d_6.

The triszwitterionic precursor **11** was obtained in four steps according to the synthetic procedure illustrated in Scheme 1. The synthesis of trismalonic ester **8** was achieved in 50% yield by a palladium-catalysed coupling of 1,3,5-tris(4-phenylbromo)benzene with sodium diethyl malonate in toluene. Subsequently, compound **8** was hydrolyzed to form the hexacarboxylic acid **9** in 98% yield. Conversion of **9** into its corresponding acyl halide **10**, followed by coupling of **10** with *N,N'*-bis(2,6-di-isopropyl-phenyl) formamidine led to the zwitterionic salt **11** with a yield of 47%. The triszwitterionic salt was characterized by ^{1}H and ^{13}C NMR spectroscopy and elemental analysis. The ^{1}H NMR spectrum of **11** shows the characteristic N*CH*N signal at δ 9.87 ppm in DMSO-d_6 (δ 8.15 ppm in CDCl$_3$). The symmetric nature of **11** was evident in the ^{1}H and ^{13}C NMR spectra.

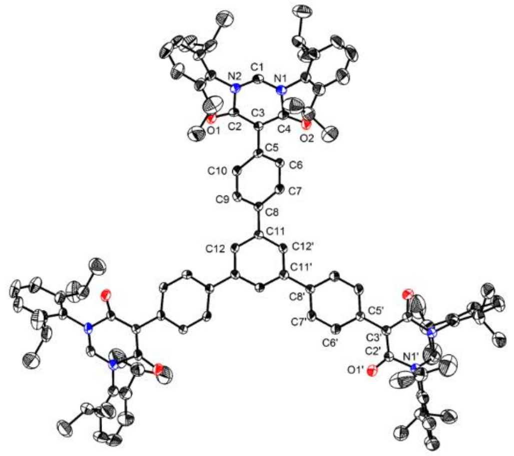
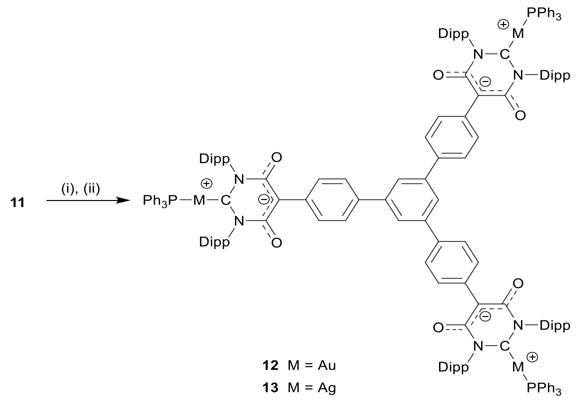


Fig. 3 Solid state molecular structure of **11** with 50% probability ellipsoids. Hydrogen atoms and solvent molecules are omitted for clarity. The twofold axis bisects the molecule through C1', C5', C8', C11', and C12. Selected bond lengths (Å) and angles (deg): N1-C1 1.312(5), N2-C1 1.308(5), C1'-N1' 1.306(4), N2-C1-N1 122.8(3), N1'-C1'-N1' 123.2(5).

Single crystals of **11** for X-ray diffraction studies were obtained by slow evaporation of a saturated solution of **11** in a mixture of chloroform–toluene at room temperature. The structure analysis revealed the expected molecular structure of triszwitterionic salt as shown in Figure 3. The salt crystallizes in the space group $P3_121$ as a [**11**] · 3 $C_6H_5CH_3$ solvate. The unit cell has a high symmetry, and the molecule itself has two-fold symmetry. The average N-C1 distance (1.308 Å) and the N-C-N angle (122.9°) fall in the ranges previously reported for its mono- and bis-*malo*NHC analogues.[6-7] Two of the pyrimidine rings are almost coplanar with the central benzene moiety (2.7° dihedral angle), while the third pyrimidine ring is twisted by 46.8° relative to the same central ring. As expected, the N-CO bonds (average distance 1.459 Å) are very long for amide functionalities, a consequence of the competitive delocalization within the malonate fragments, which presumably reduces the multiple bond character of the amidic C-N bonds. An interesting feature of this structure is the average distance between the hydrogen atoms of the NCHN moieties of 18.888 Å. This distance is longer than the average distances found in the corresponding azolium salt precursors of the neutral tris-NHCs **1**-**4** (which range between 10.9-15.4 Å),[5] an indication that the coordinated tris-NHC **7** is prone to display the longest average metal-metal distance of them all.

To access the target carbene **7**, deprotonation of **11** was attempted with potassium bis(trimethylsilyl)amide (KHMDS) in DMSO-d_6 in an NMR experiment. The reaction proceeded cleanly to afford **7**, which was stable enough to be characterized by NMR spectroscopy. The ^{1}H NMR spectrum of the reaction mixture revealed that the signal due to NC*H*N protons at δ 9.87 ppm had disappeared. The ^{1}H and ^{13}C spectra indicate a molecule with 3-fold symmetry. The carbene carbons exhibited a single ^{13}C NMR chemical shift at δ = 242.5 ppm, a 95.1 ppm downfield shift relative to **11**. Carbene **7** displays the same chemical shift as that displayed by the terphenylene-bridged Janus carbene **6**.[7] The free carbene was isolated quantitatively from the reaction mixture and it was found to be stable for at least several days under inert conditions at room temperature. Unfortunately, repeated attempts to isolate a single crystal of **7** suitable for X-ray diffraction analysis were unsuccessful, in part due to the very low solubility of the free carbene in any solvent other than DMSO.



Scheme 2 Syntheses of trimetallic complexes **12** and **13**. Conditions: (i) KHMDS, THF; (ii) PPh_3AuCl or PPh_3AgOTf in THF.

To investigate the nucleophilic behaviour of **7**, two different homotrimetallic complexes of gold (I) and silver (I) were targeted. The complexation of **7** was achieved by the addition of PPh_3AuCl or PPh_3AgOTf precursors to the *in situ* generated triscarbene in THF (Scheme 2). The desired complexes **12** and **13** were obtained in moderate yields (57% and 71%, respectively) after purification by column chromatography. Both complexes were characterized by ^{1}H and ^{13}C NMR spectroscopy and elemental analysis. The carbene carbons of the gold complex **12** were detected as a doublet at δ = 201.5 ppm ($J_{P\text{-}C}$ = 119.8 Hz), while the carbene carbons of the silver complex **13** appear as two doublets of doublets centered at 200.9 ppm, consistent with splitting by the three ½ nuclei (^{107}Ag, ^{109}Ag, and ^{31}P). The ^{13}C-^{107,109}Ag coupling constants are large (201.2 and 231.1 Hz, respectively) and suggest that **13** does not experience rapid ligand exchange on the NMR time scale in CD_2Cl_2. The chemical shifts of the carbonic carbons of **7** and of its mono- and bis-*malo*NHC analogues, in both free and coordinated forms, suggest that the reactivity and the affinity of each carbene "face" of **7** towards transition metals do not deviate abnormally from that of their mono- and ditopic analogues.[6]

The molecular structures of **12** and **13** were determined by X-ray diffraction studies. Suitable single crystals of both compounds were obtained by slow evaporation of saturated solutions of **12** and **13** in a mixture of dichloromethane-benzene at room temperature. Both complexes crystallize as benzene solvates ([**12**] · 2.5 C_6H_6 and [**13**] · 2 C_6H_6, respectively). The reduced cell parameters of **12** and **13** are similar, but differ from one another just enough to impart different symmetry and slightly different packing in the two structures.

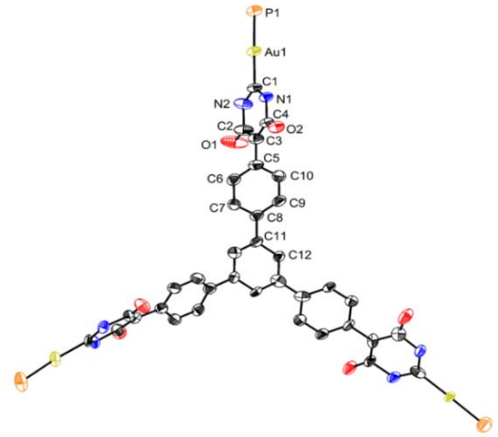


Fig. 4 Solid state molecular structure of **12** with 50% probability ellipsoids. Hydrogen atoms, phenyl rings of PPh_3, Dipp groups, and solvent molecules are omitted for clarity. Selected bond lengths (Å) and angles (deg): Au1-C1 2.050(9), Au1-P1 2.281(3), N1-C1 1.346(13), N2-C1 1.319(13), N1-C1-N2 116.6(9), C1-Au1-P1 177.3(3). We note that all the atoms shown, including unlabelled atoms, are unique for the structure in *P*-1, and the bond lengths for those atoms not labelled are comparable to those summarized here. The labels of C1'-C12' and C1''-C12'' are omitted for clarity to emphasize the molecular shape.

The gold complex **12** crystallizes in space group *P*-1 (Figure 4), while the silver complex **13** crystallizes in space group *C*2/*c* (see ESI). The metal centers display linear coordination geometries with an average C1-Au1-P1 angle of 177.03° and C1-Ag1-P1 of 177.26°. The N1-C1-N2 angles of **12** and **13** exhibit smaller N1-C1-N2 average values (117.02° and 116.89°, respectively) than the same angle of the corresponding zwitterionic precursor **11**. The average Au-C1 and Ag-C1 bond distances are 2.066 and 2.129 Å, respectively, and they are comparable with those reported for the corresponding metal complexes of carbenes **5** and **6**. The intramolecular distance between the three carbene centers of **12** and **13** is about 17.3 Å. The three gold atoms in **12** form a triangle featuring an average Au···Au separation of 20.89 Å, while the average Ag···Ag distance of **13** is 21.03 Å. The Au···Au distance displayed by **12** is about 7 Å longer than that determined for the reported gold complexes of carbenes **1** and **3** (13.4 and 13.6 Å, respectively)[5b, 5f] and, it is estimated to be about 3.5 Å longer than a corresponding possible gold complex derived from trisNHC **2**. To our knowledge, this is the longest metal-metal separation distance reported so far for a Cerberus-type tris(NHC) ligand.

In summary, this paper describes the synthesis and reactivity of the first trisanionic Cerberus-type NHC combining three equilaterally opposed *malo*NHCs. Formation of the free carbene **7** was confirmed by ^{1}H and ^{13}C NMR spectroscopy. This trisNHC provides access to neutral complexes of monocationic metals bearing otherwise neutral ligands, a feature not available with the current arsenal of neutral Cerberus-type carbenes. The utility of **7** as a bridging ligand was established by its incorporation in two new trinuclear coinage metal complexes (gold complex **12** and silver complex **13**). These complexes have been characterized by ^{1}H, ^{13}C, and ^{31}P NMR spectroscopy, as well as elemental analysis and X-ray crystallography. They exhibit the longest average metal-to-metal through-space distance for a Cerberus type-carbene reported to date (20.89 Å for Au···Au and 21.03 Å for Ag···Ag). Due to its unique geometrical and electronic properties, this new trisNHC has the potential to serve as building block for the preparation of an assortment of functional organic and metal-organic frameworks, microporous polymers, and porous organic molecular solids, systems not accessible from the neutral Cerberus-type NHCs. Further efforts to incorporate this carbene in other homo- and heterotrimetallic complexes and zwitterionic metal-organic frameworks are currently underway in our laboratory.

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Conflicts of Interest

There are no conflicts to declare.

Notes and references

1 (a) A. J. Arduengo, III, R. L. Harlow and M. J. Kline, *J. Am. Chem. Soc.* 1991, **113**, 361.

2 (a) F. Glorius, *N-Heterocyclic Carbenes in Transition Metal Catalysis, Vol. 21*, Springer-Verlag, Berlin/Heidelberg, **2007**; (b) L. Mercs and M. Albrecht, *Chem. Soc. Rev.* 2010, **39**, 1903; (c) S. P. Nolan, *N-Heterocyclic Carbenes in Synthesis*, Wiley-VCH, Weinheim, Germany, **2006**; (d) L. Oehninger, R. Rubbiania and I. Ott, *Dalton Trans.* 2013, **42**, 3269; (e) I. Ott, in *Inorganic and Organometallic Transition Metal Complexes with Biological Molecules and Living Cells* (Ed.: K. K.-W. Lo), Academic Press, **2017**, pp. 147.

3 (a) A. J. Boydston and C. W. Bielawski, *Dalton Trans.* 2006, 4073; (b) A. J. Boydston, J. D. Rice, M. D. Sanderson, O. L. Dykhno and C. W. Bielawski, *Organometallics* 2006, **25**, 6087; (c) A. J. Boydston, K. A. Williams and C. W. Bielawski, *J. Am. Chem. Soc.* 2005, **127**, 12496; (d) D. J. Coady, D. M. Khramov, B. C. Norris, A. G. Tennyson and C. W. Bielawski, *Angew. Chem., Int. Ed.* 2009, **48**, 5187; (e) O. Guerret, S. Sole, H. Gornitzka, M. Teichert, G. Trinquier and G. Bertrand, *J. Am. Chem. Soc.* 1997, **119**, 6668; (f) J. W. Kamplain and C. W. Bielawski, *Chem. Commun.* 2006, 1727; (g) D. M. Khramov, A. J. Boydston and C. W. Bielawski, *Angew. Chem., Int. Ed.* 2006, **45**, 6186; (h) S. Langbein, H. Wadepohl and L. H. Gade, *Organometallics* 2016, **35**, 809; (i) E. Mas-Marzá, J. A. Mata and E. Peris, *Angew. Chem., Int. Ed.* 2007, **46**, 3729; (j) L. Mercs, A. Neels and M. Albrecht, *Dalton Trans.* 2008, 5570; (k) A. Prades, E. Peris and M. Alcarazo, *Organometallics* 2012, **31**, 4623; (l) M.-M. Gan, J.-Q. Liu, L. Zhang, Y.-Y. Wang, F. E. Hahn, Y.-F. Han, *Chem Rev*. 2018, **118**, 9587; (m) N. Sinha and F. E. Hahn, *Acc. Chem. Res.* 2017, **50**, 2167.

4 (a) F. M. Conrady, R. Fröhlich, C. Schulte to Brinke, T. Pape and F. E. Hahn, *J. Am. Chem. Soc.* 2011, **133**, 11496; (b) M. Nussbaum, O. Schuster and M. Albrecht, *Chem. Eur. J.* 2013, **19**, 17517; (c) A. Rit, T. Pape and F. E. Hahn, *J. Am. Chem. Soc.* 2010, **132**, 4572; (d) M. Schmidtendorf, T. Pape and F. E. Hahn, *Angew. Chem., Int. Ed.* 2012, **51**, 2195; (e) M. Schmidtendorf, C. Schulte to Brinke and F. E. Hahn, *J. Organomet. Chem.* 2014, **751**, 620; (f) O. Schuster, L. Mercs and M. Albrecht, *Chimia* 2010, **64**, 184; (g) A. G. Tennyson, B. C. Noris and C. W. Bielawski, *Macromolecules* 2010, **43**, 6923; (h) H. Valdes, M. Poyatos and E. Peris, *Organometallics* 2015, **34**, 1725; (i) M. Viciano, M. Sanaú and E. Peris, *Organometallics* 2007, **26**, 6050; (j) K. A. Williams, A. J. Boydston and C. W. Bielawski, *Chem. Soc. Rev.* 2007, **36**, 729; (k) A. Zanardi, R. Corberán, J. A. Mata and E. Peris, *Organometallics* 2008, **27**, 3570.

5 (a) S. Gonell, R. G. Alabau, M. Poyatos and E. Peris, *Chem. Commun.* 2013, **49**, 7126; (b) S. Gonell, M. Poyatos and E. Peris, *Angew. Chem., Int. Ed.* 2013, **52**, 7009; (c) S. Gonell, M. Poyatos and E. Peris, *Chem. Eur. J.* 2014, **20**, 5746; (d) S. Ibáñez, M. Poyatos and E. Peris, *Chem. Commun.* 2017**, 53**, 3733; (e) C. Segarra, J. Linke, E. Mas-Marza, D. Kuck and E. Peris, *Chem. Commun.* 2013, **49**, 10572; (f) Y.-T. Wang, M.-T. Chang, G.-H. Lee, S.-M. Peng and C.-W. Chiu, *Chem. Commun.* 2013, **49**, 7258; (g) K. A. Williams and C. W. Bielawski, *Chem. Commun.* 2010, **46**, 5166.

6 D. Tapu, Z. McCarty, and C. McMillen, *Chem. Commun.* 2014, **50**, 4725.

7 A. Carter, A. Mason, M. A. Baker, D. G. Bettler, A. Changas, C. D. McMillen and D. Tapu, *Organometallics* 2017, **39**, 1867.

8 (a) V. César, C. Barthes, Y. C. Farré, S. V. Cuisiat, B. Y. Vacher, R. Brousses, N. Lugan and G. Lavigne, *Dalton Trans.* 2013, **42**, 7373; (b) V. César, L. C. M. Castro, T. Dombray, J.-B. Sortais, C. Darcel, S. Labat, K. Miqueu, J.-M. Sotiropoulos, R. Brousses, N. Lugan and G. Lavigne, *Organometallics* 2013, **32**, 4643; (c) V. César, S. Labat, K. Miqueu, J.-M. Sotiropoulos, R. Brousses, V. Lugan and G. Lavigne, *Chem. Eur. J.* 2013, **19**, 17113; (d) V. César, N. Lugan and G. Lavigne, *J. Am. Chem. Soc.* 2008, **130**, 11286; (e) V. César, N. Lugan and G. Lavigne, *Eur. J. Inorg. Chem.* 2010, 361; (f) V. César, N. Lugan and G. Lavigne, *Chem. Eur. J.* 2010, **16**, 11432; (g) M. G. Hobbs, C. J. Knapp, P. T. Welsh, J. Borau-Garcia, T. Ziegler and R. Roesler, *Chem. Eur. J.* 2010, **16**, 14520; (h) M. Henrion, B. de P. Cardoso, V. César, M. J. Chetcuti and V. Ritleng, *Organometallics* 2017, **36**, 1113.

9 T. Dröge and F. Glorius, *Angew. Chem., Int. Ed.* 2010, **49**, 6940.

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