



Bis-phosphine allene ligand: coordination chemistry and preliminary applications in catalysis

Avassaya Vanitcha, Cecilia Damelin court, Geoffrey Gontard, Nicolas Vanthuyne, Virginie Mouriès-Mansuy, Louis Fensterbank

► To cite this version:

Avassaya Vanitcha, Cecilia Damelin court, Geoffrey Gontard, Nicolas Vanthuyne, Virginie Mouriès-Mansuy, et al.. Bis-phosphine allene ligand: coordination chemistry and preliminary applications in catalysis. Chemical Communications, 2016, 52, pp.6785-6788 10.1039/c6cc02316a . hal-01311658

HAL Id: hal-01311658

<https://hal.sorbonne-universite.fr/hal-01311658>

Submitted on 4 May 2016

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Bis-phosphine allene ligand: coordination chemistry and preliminary applications in catalysis

Received 00th January 20xx,
 jkAccepted 00th January 20xx

Avassaya Vanitcha,^a Cecilia Damelin-court,^a Geoffrey Gontard,^a Nicolas Vanthuyne,^b Virginie Mouriès-Mansuy^{a*} and Louis Fensterbank^{a*}

DOI: 10.1039/x0xx00000x

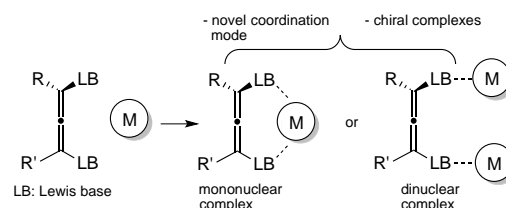
www.rsc.org/

A 1,3-bis-diphenylphosphine allene can give birth to new coordination complexes with palladium, platinum and gold metals. These complexes were fully characterized by NMR, HRMS and X-ray diffraction analysis. For gold(I), the corresponding dinuclear complex has been used in a series of diagnostic catalytic reactions and gave promising preliminary results in asymmetric catalysis.

Coordination chemistry has been at the center of chemists' preoccupations since the pioneering works of Christian Wilhem Blomstrand, Sophus Mads Jorgensen and Alfred Werner in the 19th century. This very fundamental and intense domain of investigation has continuously irrigated several fields of applications such as catalysis, material sciences, supramolecular and medicinal chemistry.¹ Based on the interaction between a ligand and a metal center, the game of combining both components appears unlimited and the number of existing coordination adducts is still restricted, leaving a vast unexplored chemical space. Nevertheless, a rationale design is desirable to guarantee the preparation of objects with optimized properties. This approach generally requires to start from elementary building blocks (ligand or metal) with peculiar attributes.

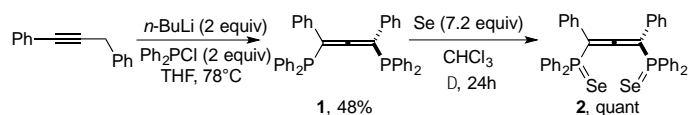
Thus, thanks to its unique stereoelectronic features, an allene scaffold bearing Lewis base and possibly conveying some chiral information sites appeared to us as a valuable keystone (Scheme 1).² As further incentive, there has been, to the best of our knowledge, a very limited number of allene-derive ligands involved in metallic coordination complexes. Krause reported the formation of silver and copper complexes from allene-containing bipyridine ligands, but no catalytic activity was reported.³ Chiral diphosphine oxide allenes were first used as

organocatalysts by Ready who described the highly enantioselective formation of epichlorhydrines from *meso*-epoxides with SiCl₄.⁴ Later, the same group devised chiral allene-containing bisphosphines, that when coordinated to Rh(I), were able to promote the asymmetric addition of arylboronic acids to α -keto esters with high enantioselectivity.⁵



Scheme 1 New prospects in coordination chemistry with allene ligands

In line with this strategy, our attention was drawn to bis-phosphine 1,3-bis(diphenylphosphino)-1,3-diphenylallene **1** featuring direct attachment of the phosphorus moieties on the allene scaffold, which has been so far very rarely encountered.⁶ The Schmidbaur group previously described the synthesis of **1**.⁷ Following their procedure, we obtained **1** in a consistent yield of 48 % (Scheme 2).



Scheme 2 Allene bisphosphine **1** and its bis-seleno derivative **2**

We then studied the unexplored coordination properties of **1** and focused on the possibility of obtaining mononuclear palladium (II) and platinum (II) complexes. Thus, heating at 80°C for 4 h a 1:1 mixture of bis(acetonitrile)dichloropalladium and **1** in toluene afforded the coordination complex **3** (84% yield) that was isolated as an orange solid after precipitation in cold ether. ³¹P NMR showed a singlet peak resonance at δ_P = 128.3 ppm, very downfield compared to the starting allene **1** (δ_P = 33.2 ppm) and the ¹³C peak of the central allene carbon was

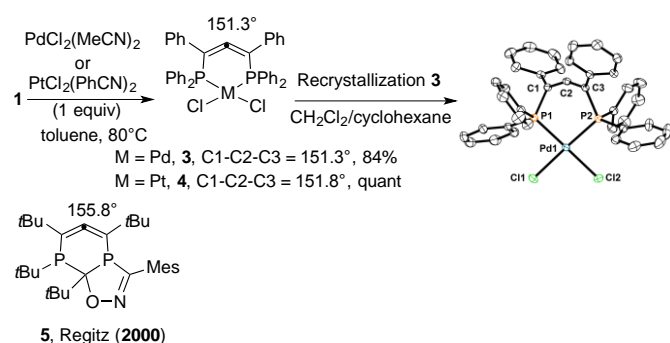
^a Sorbonne Universités UPMC Univ Paris 06, CNRS, UMR 8232, Institut Parisien de Chimie Moléculaire, 4 place Jussieu, C.229, F-75005 Paris, France

^b Aix-Marseille Université, Centrale Marseille, CNRS, iSm2 UMR 7313, 13397, Marseille, France

† Dedicated to Antonio Echavarren

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

observed as a triplet peak (t , $^2J_{CP} = 3.8$ Hz) at 193.3 ppm (δ , $^1J_{CP} = 3.5$ Hz) for **1**). An initial crystallization attempt of the bis-P-coordinated Pd allene complex **3** in MeOH provided suitable material for a single crystal X-ray diffraction (XRD) analysis. Interestingly, the latter showed a co-crystallized mixture of MeOH and HCl adducts on **3** (see SI). While these findings strongly suggested the formation of the Pd-allene complex **3**, its structure was fully confirmed after XRD analysis of crystals grown in a $\text{CH}_2\text{Cl}_2/\text{cyclohexane}$ mixture.⁸ A square planar coordination was observed. More striking was the severely bent character of the allene moiety, exhibiting a $\text{C}=\text{C}=\text{C}$ bond angle of $151.2(2)^\circ$. The C1-C2 and C2-C3 bond lengths of respectively 1.303(3) and 1.315(3) Å lie in the typical range observed for cumulenes.⁹



Scheme 3 Pd and Pt mononuclear complexes with ligand **1**

Similarly, platinum complex **4** was formed quantitatively.³¹ P NMR shows a central resonance at $\delta_P = 98.7$ ppm with two small satellite peaks due to ^{195}Pt ($^1J_{P-^{195}\text{Pt}} = 4371$ Hz). Here also, the ^{13}C peak of the allene central carbon is more shielded ($\delta = 198.9$ ppm, $^2J_{CP} = 5.1$ Hz). The XRD analysis⁸ confirmed the structure and also showed a square planar coordination with a similar $\text{C}=\text{C}=\text{C}$ bent angle of $151.8(4)^\circ$ (see SI).

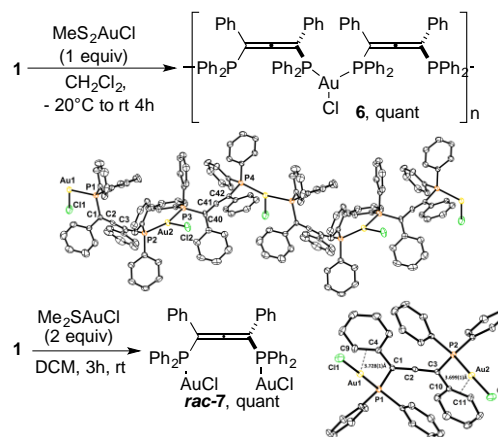
A few bent allenes have previously been reported¹⁰ though there has been some controversy in assigning an allenic character to some of them.¹¹ The most structurally related example to **3** or **4** corresponds to cyclic allene **5**, previously isolated by Regitz and exhibiting a $\text{C}=\text{C}=\text{C}$ angle of 155.8° .^{6c} While palladium complex **3** appears quite stable, platinum complex **4** decomposed in few days upon standing on the bench at rt.

These preliminary findings validated the coordination ability of allene **1** so we looked at the possible formation of gold complexes in connection with our interest in gold catalysis.^{12,13}

Our initial attempt focused on the formation of a tricoordinate mononuclear complex as more and more examples¹⁴ of this coordination mode have been reported and shown intriguing properties.¹⁵ Interestingly, when mixing 1.1 equiv of **1** with 1 equiv of Me_2SAuCl in CH_2Cl_2 at -20°C , a new species ($\delta_P = 12.5$ ppm, broad peak) was selectively formed. The XRD analysis revealed the polymeric gold complex **6**.^{16,17} While the properties of these macromolecular objects will be studied, we turned our attention on dinuclear complexes.

Thus, treatment of **1** with 2 equiv of Me_2SAuCl in CH_2Cl_2 provided quantitatively the chiral gold(I) complex **rac-7**. The latter proved to be quite stable to air and moisture. Its structure

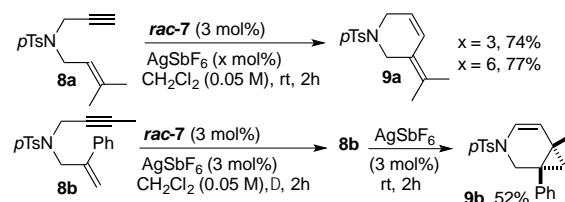
was also confirmed by XRD studies (Scheme 4).¹⁷ Despite the known carbophilicity of gold(I) salts,¹⁸ coordination took place exclusively on the phosphine moieties, leaving the allene unaltered. The two Au atoms lie in opposite direction, with an Au-Au distance of 6.498(1) Å precluding any aurophilic interaction.¹⁹ The distance between the Au atom and the phenyl group of the allene moiety is, on average, 3.71(2) Å suggesting no η^1 or η^2 interaction as described for the JohnPhos gold(I) chloride complex and congeners.²⁰



Scheme 4 Mononuclear and dinuclear gold(I) complexes

The evaluation of the electronic properties of allene **1** was achieved by measuring the magnitude of $^1J_{P-Se}$ on the ^{77}Se isotopomer²¹ of the corresponding bis-selenide derivative **2** (Scheme 2). With a $^1J_{P-Se}$ value of 754 Hz, allene **1** exhibits an intermediate σ -donor ability, lower than PPh_3 ($^1J_{P-Se} = 728$ Hz) but much higher than P(PhO)_3 ($^1J_{P-Se} = 1027$ Hz).²²

We then evaluated the catalytic activity of gold complex **rac-7** using the prototypical *N*-tethered 1,6-enyne precursor **8a**. The reaction was carried out in CH_2Cl_2 with a catalytic 1:1 mixture of **rac-7** (3 mol%) and AgSbF_6 to afford diene **9a** in 74% yield. When 1,6 enyne **8b** was treated in the same conditions, only starting material was recovered even in refluxing conditions. An additional 3 mol% of silver salt gave the expected product **9b** in 52% yield. It is noteworthy that when 2 equiv of AgSbF_6 (6 mol%) were introduced right from the start of the reaction, compound **9a** was obtained in similar yield as with 3 mol% but we observed a better yield (85%) for compound **9b** (Scheme 5).

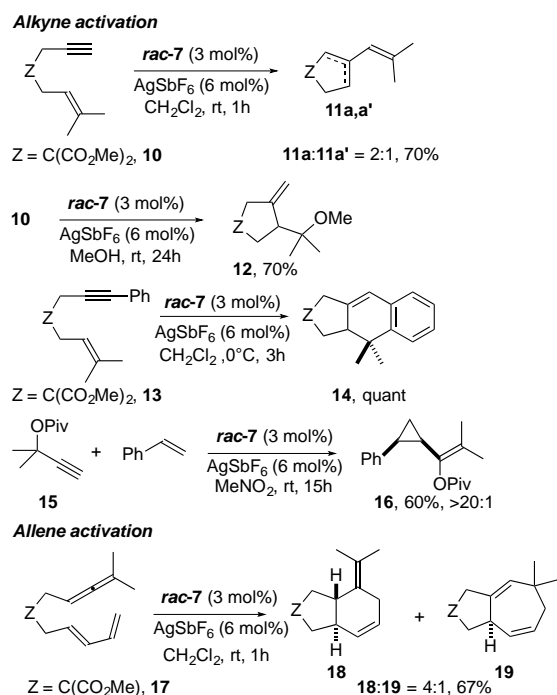


Scheme 5 Preliminary catalytic testing

As previously reported in the literature²³ and by us,²⁴ we suspected the detrimental formation of a chloride-bridged digold complex. The latter was detected by ESI MS at 20V (see SI) from an equimolar mixture of **1** and AgSbF_6 in CH_2Cl_2 , as

attested by the presence of a peak at m/z 989 ($C_{39}H_{30}Au_2ClP_2^+$). This complex would be cleaved by more coordinating substrates like **8a** or by the addition of an excess of silver salt yielding a dicationic gold catalytic species.

Following the previously defined reaction conditions, we extended the investigation on the electrophilic catalytic properties of **rac-7** by examining the reactivity of several representative polyunsaturated substrates. Thus, enyne **10** provided regioselectively cyclopentadienic dienes **11a,a'**²⁵ in 70% yield with no cyclohexadienic product.^{13c} Running the same reaction in methanol as solvent did not affect the catalytic activity and gave smoothly methoxycyclization adduct **12** as a single regioisomer.²⁵ The quantitative conversion of enyne **13** into tricyclic derivative **14** confirmed the robustness of this catalytic system.²⁶

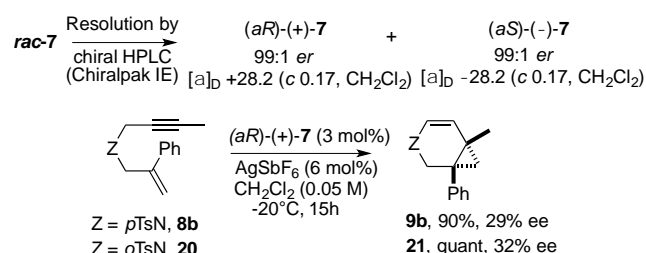


Scheme 6 Scope of the catalysis with **rac-7**

Intermolecular gold catalyzed additions offer interesting synthetic opportunities. We evaluated the intermolecular cyclopropanation reaction between propargyl pivalate **15** and styrene and were pleased to obtain cyclopropane adduct **16** in 60% yield and in a improved diastereoselectivity (>20:1) in favor of the *cis*-isomer than previously reported (>6:1).²⁷ The cycloisomerization of allenediene **17** served as a very informative probe. It showed that the chemoselective activation of an allene was possible with our allene-based catalytic system since a 4:1 mixture of [4+2] and [4+3] cycloadducts **18** and **19** was obtained in 67% yield. The major formation of **18** suggests a rather electron depleted catalytic species, more electrophilic than with triphenylphosphine as ligand which gives a 2 : 1 ratio of **18** and **19**.²⁸ This product distribution is thus consistent with our preliminary evaluation of the electronics with bis-seleno derivative **2** (Scheme 6).

We finally wished to look at the opportunity to use the chirality of ligand **1** for asymmetric transformations.²⁹ Although the number of optical resolutions of organometallic complexes by preparative HPLC remains limited,³⁰ and to the best of our knowledge none with gold,³¹ we tried this method on the gold chloride complex **rac-7**. Gratifyingly, the enantiomers of complex **rac-7** were nicely separated by analytical chiral chromatography on Chiralpak IE column. Each enantiomer was obtained with high 98% ee and their absolute configuration determined by anomalous XRD.³² We then evaluated the catalytic activity of (*aR*)-(+)-**7** for the asymmetric cycloisomerisation of 1,6-enynes **8b** and **20**. The expected aza bicyclo[4.1.0]heptenes **9b** and **21** were obtained in good yields and in promising ees of 29 and 32 %, respectively (Scheme 7).

Scheme 7 Resolution and asymmetric catalysis



Conclusions

This journey in the coordination of bis-phosphine allene **1** with palladium, platinum and gold salts has allowed the formation of highly novel and original coordination complexes. Physico-chemical properties of these complexes will be pursued. Focusing on gold(I) salts, we could generate a new type of chiral dinuclear gold precatalyst. The precatalyst **rac-7** in the presence of a silver salt proved to be very competent and robust in a series of prototypical gold-catalyzed reactions. Investigation of the electronic properties suggests a moderately electrophilic gold complex which was corroborated by catalytic results. Preliminary testing of the corresponding optically pure complex obtained by preparative chiral HPLC gave promising hits for asymmetric catalysis. It is anticipated that fine electronic and steric tuning of the allene bis-phosphine ligand by appropriate substitution should boost the catalytic properties.

Notes and references

- 1 a) *Comprehensive Coordination Chemistry II* (Eds.: J. A. McCleverty, T. J. Meyer, Elsevier (Boston), **2004**; b) *Comprehensive Organometallic Chemistry 3rd edition* (Eds.: R. H. Crabtree, D. M. P. Mingos), Elsevier, **2007**; c) *Bioorganometallic Chemistry: Applications in Drug Discovery, Biocatalysis and Imaging* (Eds.: G. Jaouen, M. Salmann, Wiley, **2015**; d) M. Han, D. M. Engelhard, G. H. Clever, *Chem. Soc. Rev.* **2014**, 43, 1848; e) M. M. J. Smulders, I. A. Riddell, C. Browne, J. R. Nitschke, *Chem. Soc. Rev.* **2013**, 42, 1728; f) K. Harris, D. Fujita, M. Fujita, *Chem. Commun.* **2013**, 49, 6703; g) T. R. Cook, Y. R. Zheng, P. J. Stang, *Chem. Rev.* **2013**, 113, 734; h) D. L. Caulder, K. N. Raymond, *Acc. Chem. Res.* **1999**, 32, 975; g) C. G. Hartinger, N. Metzler-Nolte and P. J. Dyson, *Organometallics* **2012**, 31, 5677.
- 2 a) *Modern Allene Chemistry* (Eds.: N. Krause, A. S. K. Hashmi), Wiley-VCH, Weinheim, **2004**; b) S. Yu and S. Ma, *Angew. Chem. Int. Ed.* **2012**, 51, 3074.

- 3 S. Löhr, J. Averbek, M. Schürmann and N. Krause, *Eur. J. Inorg. Chem.*, **2008**, 552.
- 4 X. Pu, X. Qi and J. M. Ready, *J. Am. Chem. Soc.* **2009**, *131*, 10364.
- 5 F. Cai, X. Pu, X. Qi, V. Lynch, A. Radha and J. M. Ready, *J. Am. Chem. Soc.* **2011**, *133*, 18066.
- 6 a) H. Schmidbaur and T. Pollock, *Angew. Chem. Int. Ed.* **1986**, *25*, 348; b) H. Schmidbaur, T. Pollock, G. Reber and G. Müller, *Chem. Ber.* **1987**, *120*, 1403; c) M. A. Hofmann, U. Bergsträßer, G. J. Reiß, L. Nyulászi and M. Regitz, *Angew. Chem. Int. Ed.* **2000**, *39*, 1261; d) G. Gangadhararao, R. N. P. Tulichula, K. and C. K. Swamy, *Chem. Commun.* **2015**, *51*, 7168.
- 7 H. Schmidbaur, C. M. Frazão, G. Reber and G. Müller, *Chem. Ber.* **1989**, *122*, 259.
- 8 3 CCDC 1448365; 4 CCDC 1448367.
- 9 R. P. Johnson, *Chem. Rev.* **1989**, *89*, 1111.
- 10 a) D. S. Patel and P. V. Bharatam, *J. Org. Chem.* **2011**, *76*, 2558; b) E. Weber, W. Seichter, B. Hess, G. Will and H. J. Dasting, *J. Phys. Org. Chem.* **1995**, *8*, 94; c) see also in ref. 5: a Pt(allyl monophosphine) complex showed a severely bent allene (C=C=C angle of 152°) due to a Pt-allene interaction.
- 11 a) V. Lavallo, C. A. Dyker, B. Donnadiou and G. Bertrand, *Angew. Chem. Int. Ed.* **2009**, *48*, 1540; b) M. Christl and B. Engels, *Angew. Chem. Int. Ed.* **2009**, *48*, 1538.
- 12 a) R. Dorel and A. M. Echavarren, *Chem. Rev.* **2015**, *115*, 9028; b) M. Jia and M. Bandini, *ACS Catal.* **2015**, *5*, 1638; c) D. Qian, J. Zhang, *Chem. Soc. Rev.* **2015**, *44*, 677; d) See also a special Gold Catalysis issue of *Account of Chemical Research (Acc. Chem. Res.)* **2014**, *47*, issue 3, Eds: C. Friend, A. S. K. Hashmi; e) D. Pflästerer and A. S. K. Hashmi, *Chem. Soc. Rev.* **2016**, *45*, 1331.
- 13 a) D. Leboeuf, A. Simonneau, C. Aubert, M. Malacria, V. Gandon and L. Fensterbank *Angew. Chem. Int. Ed.* **2011**, *50*, 6868; b) A. Simonneau, F. Jaroschik, D. Lesage, M. Karanik, R. Guillot, M. Malacria, J.-C. Tabet, J.-P. Goddard, L. Fensterbank, V. Gandon and Y. Gimbert, *Chem. Sci.* **2011**, *2*, 2417; c) M. Guitet, P. Zhang, F. Marcelo, C. Tugny, J. Jimenez-Barbero, O. Buriez, C. Amatore, V. Mouriès-Mansuy, J.-P. Goddard, L. Fensterbank, Y. Zhang, S. Roland, M. Ménand and M. Sollogoub, *Angew. Chem. Int. Ed.* **2013**, *52*, 7213; d) F. Nzulu, A. Bontemps, J. Robert, M. Barbazanges, L. Fensterbank, J.-P. Goddard, M. Malacria, C. Ollivier, M. Petit, J. Rieger and F. Stoffelbach, *Macromolecules* **2014**, *47*, 6652; e) A. Simonneau, Y. Harrak, L. Jeanne-Julien, G. Lemièrre, V. Mouriès-Mansuy, J.-P. Goddard, M. Malacria and L. Fensterbank, *ChemCatChem* **2013**, *5*, 1096; f) L. Ferrand, N. Das Neves, M. Malacria, V. Mouriès-Mansuy, C. Ollivier and L. Fensterbank, *J. Organomet. Chem.* **2015**, *795*, 53.
- 14 a) O. Crespo, M. C. Gimeno, A. Laguna and P. G. Jones, *J. Chem. Soc. Dalton Trans* **1992**, 1601; b) M. C. Gimeno and A. Laguna, *Chem. Rev.* **1997**, *97*, 512.
- 15 a) For a review, see: M. Joost, A. Amgoune and D. Bourissou, *Angew. Chem. Int. Ed.* **2015**, *54*, 15022; b) J. G. Guenther, S. Mallet-Ladeira, L. Estevez, K. Miqueu, A. Amgoune and D. Bourissou, *J. Am. Chem. Soc.* **2014**, *136*, 1778; c) H. Yang, F. P. Gabbai, *J. Am. Chem. Soc.* **2015**, *137*, 13425.
- 16 For Au(I)-based polymeric chains, see: a) S. H. Lim, M. L. Olmstead and A. L. Balch, *J. Am. Chem. Soc.* **2011**, *133*, 10229; b) V. J. Catalano, M. A. Malwitz, S. H. Horner and J. Vasquez, *Inorg. Chem.* **2003**, *42*, 2141; c) M. Streitberger, A. Schmied and E. Hey-Hawkins, *Inorg. Chem.* **2014**, *53*, 6794; d) L.-T. Phang, T. S. A. Hor, Z.-Y. Zhou and T. C. W. Mak, *J. Organometal. Chem.* **1994**, *469*, 253; e) C. Khin, A. S. K. Hashmi and F. Rominger, *Eur. J. Inorg. Chem.* **2010**, 1063.
- 17 6 CCDC 1448368; *rac-7* CCDC 1448369.
- 18 For reviews on the coordination of gold salts onto allenes: a) M. Malacria, L. Fensterbank and V. Gandon, *Top. Curr. Chem.* **2011**, *302*, 157; b) E. Soriano and I. Fernandez, *Chem. Soc. Rev.* **2014**, *43*, 3041; c) W. Yang and A. S. K. Hashmi, *Ibid.* **2014**, *43*, 2941; For coordination complexes, see: d) A. Fürstner, M. Alcarazo, R. Goddard, C. W. Lehmann, *Angew. Chem. Int. Ed.* **2008**, *47*, 3210; e) T. J. Brown, A. Sugie, M. G. Leed, R. A. Widenhoefer, *Chem. Eur. J.* **2012**, *22*, 6959; for the first description of gold-catalyzed additions to allenes, see: f) A. S. K. Hashmi, L. Schwarz, J.-H. Choi and T. M. Frost, *Angew. Chem. Int. Ed.* **2000**, *39*, 2285.
- 19 a) H. Schmidbaur and A. Schier, *Chem. Soc. Rev.* **2012**, *41*, 370; b) A. S. K. Hashmi, *Acc. Chem. Res.* **2014**, *47*, 864.
- 20 P. Pérez-Galán, N. Delpont, E. Herrero-Gómez, F. Maseras and A. M. Echavarren, *Chem. Eur. J.* **2010**, *16*, 5324.
- 21 a) D. W. Allen, L. A. March and I. W. Nowell, *J. Chem. Soc. Dalton Trans.* **1984**, 483; b) D. W. Allen and B. F. Taylor, *J. Chem. Soc. Dalton Trans.* **1982**, 51; c) A. Muller, S. Otto and A. Roodt, *Dalton Trans* **2008**, 650; d) M. R. Axet, M. Barbazanges, M. Augé, C. Desmarests, J. Moussa, C. Ollivier, C. Aubert, L. Fensterbank, V. Gandon, M. Malacria, L.-M. Chamoreau and H. Amouri, *Organometallics* **2010**, *29*, 6636.
- 22 C. Glidewell and E. J. Leslie, *J. Chem. Soc. Dalton Trans.* **1977**, 527.
- 23 a) A. Bayler, A. Bauer and H. Schmidbaur, *Chem. Ber.*, **1997**, *130*, 115; b) A. Hamel, N. W. Mitzel and H. Schmidbaur, *J. Am. Chem. Soc.* **2001**, *123*, 5106; c) Y. Zhu, C. S. Day, L. Zhang, K. J. Hauser and A. C. Jones, *Chem. Eur. J.* **2013**, *19*, 12264; d) A. Homs, I. Escofet and A. M. Echavarren, *Org. Lett.* **2013**, *15*, 5782. e) Z. Lu, J. Han, G. B. Hammond and B. Xu, *Org. Lett.* **2015**, *17*, 4534.
- 24 F. Schröder, C. Tugny, E. Salanouve, H. Clavier, L. Giordano, D. Moraleda, Y. Gimbert, V. Mouriès-Mansuy, J.-P. Goddard and L. Fensterbank, *Organometallics* **2014**, *33*, 4051.
- 25 a) C. Nieto-Oberhuber, S. López, A. M. Echavarren *J. Am. Chem. Soc.* **2005**, *127*, 6178; b) C. Bartolomé, Z. Ramiro, D. García-Cuadrado, P. Pérez-Galán, M. Raducan, C. Bour, A. M. Echavarren and P. Espinet, *Organometallics* **2010**, *29*, 951; c) M. Raducan, M. Moreno, C. Bour and A. M. Echavarren, *Chem. Commun.* **2012**, *48*, 52; d) S. Ito, S. Kusano, N. Morita, K. Mikami and M. Yoshifuji, *J. Organomet. Chem.* **2010**, *695*, 291; e) M. Raducan, C. Rodríguez-Escrich, X. C. Cambeiro, E. C. Escudero-Adán, M. A. Pericás and A. M. Echavarren, *Chem. Commun.* **2011**, *47*, 4893.
- 26 C. Nieto-Oberhuber, S. López, A. M. Echavarren *J. Am. Chem. Soc.* **2005**, *127*, 6178.
- 27 M. J. Johansson, D. J. Gorin, S. T. Staben and F. D. Toste, *J. Am. Chem. Soc.* **2005**, *127*, 18002.
- 28 a) P. Mauleón, R. M. Zeldin, A. Z. González and D. Toste, *J. Am. Chem. Soc.* **2009**, *131*, 6348; b) I. Alonso, B. Trillo, F. López, S. Montserrat, G. Ujaque, L. Castedo, A. Lledós and J. L. Mascarenas, *J. Am. Chem. Soc.* **2009**, *131*, 13020; c) D. Benitez, E. Tkatchouk, A. Z. Gonzalez, W. A. Goddard III and F. D. Toste, *Org. Lett.* **2009**, *11*, 4798; d) M. Alcarazo, T. Stork, A. Anoop, W. Thiel and A. Fürstner, *Angew. Chem. Int. Ed.* **2010**, *49*, 2542.
- 29 a) A. Marinetti, H. Jullien and A. Voituriez, *Chem. Soc. Rev.* **2012**, *41*, 4884; b) A. Pradal, P. Y. Toullec and V. Michelet, *Synthesis*, **2011**, 1150; c) F. Lopez and J. L. Mascarenas, *Beilstein J. Org. Chem.* **2013**, *9*, 2250; d) W. Zi and F. D. Toste, *Chem. Soc. Rev.* **2016**, DOI: 10.1039/c5cs00929d.
- 30 a) K. Schlögl and M. Widhalm, *Chem. Ber.* **1982**, *115*, 3042; b) L. Norel, M. Rudolph, N. Vanthuyne, J. A. G. Williams, C. Lescop, C. Roussel, J. Autschbach, J. Crassous and R. Reau, *Angew. Chem. Int. Ed.* **2010**, *49*, 99; c) V. A. Soloshonok, T. Ono, H. Ueki, N. Vanthuyne, T. S. Balaban, J. Burck, H. Fliegl, W. Kloppe, J.-V. Naubron, T. T. T. Bui, A. F. Drake and C. Roussel, *J. Am. Chem. Soc.* **2010**, *132*, 10477; d) T. Tozawa, Y. Komoda, J. Ohnishi, Y. Matsuda, J. Taniuchi, C. Nakanishi and K. Okamoto, US Patent Application 5298642, **1994**; e) C. Shen, E. Anger, M. Srebro, N. Vanthuyne, L. Toupet, C. Roussel, J. Autschbach, R. Reau and J. Crassous, *Chem. Eur. J.* **2013**, *19*, 16722.
- 31 a) H. Liu, D. Leow, K.-W. Huang and C.-H. Tan, *J. Am. Chem. Soc.* **2009**, *131*, 7212; b) S. Knoppe, I. Dolamic, A. Dass and T. Bürgi, *Angew. Chem. Int. Ed.* **2012**, *51*, 7589.
- 32 (*aR*)-(+)-**7** CCDC 1448370 & (*aS*)-(–)-**7** CCDC 1448371.