Dalton Transactions

Cite this: *Dalton Trans.*, 2012, **41**, 5461

www.rsc.org/dalton

COMMUNICATION

Synthetic routes to [Au(NHC)(OH)] (NHC = *N*-heterocyclic carbene) complexes†‡

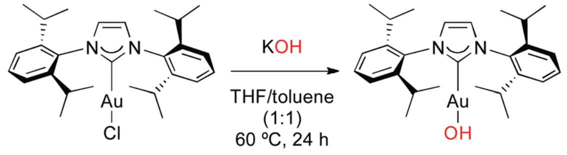
Adrián Gómez-Suárez, Rubén S. Ramón, Alexandra M. Z. Slawin and Steven P. Nolan*

Received 9th February 2012, Accepted 1st March 2012
DOI: 10.1039/c2dt30294b

New procedures for the synthesis of [Au(NHC)(OH)] are reported. Initially, a two-step reaction *via* the digold complex [{Au(NHC)}$_2$(μ-OH)][BF$_4$] was probed, enabling the preparation of the novel [Au(SIPr)(OH)] complex and of its previously reported congener [Au(IPr)(OH)]. After further optimization, a one-step procedure was developed.

Homogeneous gold catalysis has become a most intensely studied area of research during the last decade. This interest can be explained by the broad catalytic activity of gold complexes.[1] Among organometallic Au^I-catalysts, those bearing phosphines or *N*-heterocyclic carbene (NHC) ligands represent the state-of-the-art.[1] During recent years, Au-complexes bearing NHC ligands have gained increased attention as this supporting ligand class appears to stabilize coordinatively unsaturated catalytically active species.[2]

Pursuing the synthesis of new gold catalysts and following computational studies that predicted the formation of a stable Au^I–OH species, we recently reported the synthesis of [Au(IPr)-(OH)] (**1**) (IPr = 1,3-bis(2,6-diisopropyl-phenyl)imidazol-2-ylidene), the first mononuclear Au^I–hydroxide complex.[3] This new gold species was synthesized from [Au(IPr)Cl] (**2**) and KOH in a 1 : 1 mixture of THF–toluene heated at 60 °C for 24 h (eqn (1)).

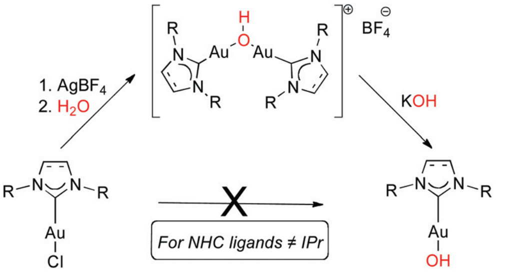


2 **1**

(1)

1 has proven a versatile synthon, granting access to a wide range of novel organogold species under mild conditions.[4] Complex **1** has been successfully used for the activation of acetylenic C–H bonds,[5] carboxylation and decarboxylation reactions,[6] and in the development of new gold-catalyzed silver-free protocols among other catalytic transformations.[7,8] Intrigued by the broad reactivity of **1**,[3–8] we forged ahead in this area and investigated the synthesis of new [Au(NHC)(OH)] complexes. Following the existing procedure using KOH, thus far only **1** had been easily isolated in pure form. As has often been the case in our studies on NHCs, IPr appears a privileged member of this family.[9] In addition, this procedure leading to **1** proved to be poorly scalable. In order to exploit the full range of gold-hydroxide chemistry; the development of new synthetic pathways was investigated.

The digold complex [{Au(IPr)}$_2$(μ-OH)][BF$_4$] (**3**),[10] discovered during the course of studies dealing with acid activation of hydroxide **1**, can be formally viewed as being composed of a cationic [Au(NHC)]$^+$ species coordinated to the oxygen of a Au-hydroxide. Hence, we envisioned a two-step procedure starting from the chloride precursor **2**, generating the digold species **3** then followed by formation of the hydroxide by addition of KOH (Scheme 1). Indeed, this digold complex has been postulated as a reactive intermediate in gold-catalyzed reactions involving water, such as nitrile and alkyne hydrations.[10,11]



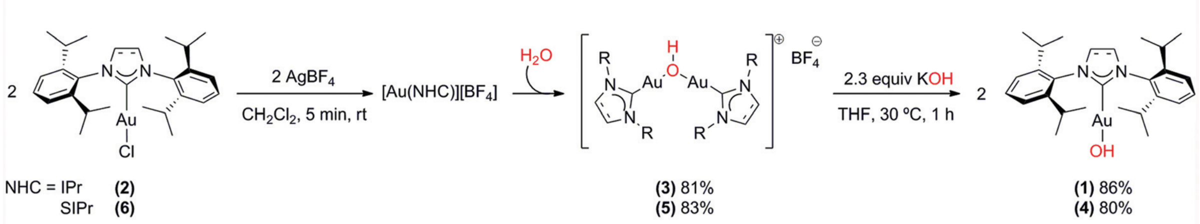
Scheme 1 Proposed synthetic route leading to [Au(NHC)(OH)].

First, the digold species **3** was synthesized by addition of AgBF$_4$ to a solution of complex **2** in dichloromethane. After filtration of the AgCl precipitate, addition of water to the intermediate [Au(IPr)][BF$_4$] afforded the digold complex **3** in 81% yield (Scheme 2). In order to validate our hypothesis that **3** could lead to **1**, 2.3 equiv of KOH were added to a solution of digold complex **3** in THF.[12] After stirring for 1 h at 30 °C,[13] ^{1}H NMR analysis of the reaction mixture confirmed full conversion to **1** which was isolated in 86% yield. Encouraged by these results and the high stability shown by the digold species, we investigated the generality of the new procedure using a NHC

EaStCHEM School of Chemistry, University of St Andrews, St Andrews, KY16 9ST, UK. E-mail: snolan@st-andrews.ac.uk; Fax: (+44)-(0)1334-463-808

† Dedicated to Professor David Cole-Hamilton on the occasion of his retirement and for his outstanding contribution to transition metal catalysis.

‡ Electronic supplementary information (ESI) available: Synthetic details and complete analytical data, NMR spectra and crystallographic data. CCDC 856432 (**4**). For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c2dt30294b



Scheme 2 Synthesis of hydroxides **1** and **4** using a two-step procedure.

relative. SIPr (SIPr = 1,3-bis(2,6-diisopropyl-phenyl)imidazolidine), the saturated version of IPr, was selected as the ligand and the synthesis of [Au(SIPr)(OH)] (**4**) was targeted next. The digold species [{Au(SIPr)}$_2$(μ-OH)][BF$_4$] (**5**)§ was synthesized first. Chloride abstraction from [Au(SIPr)Cl] (**6**) by AgBF$_4$ and subsequent reaction with water afforded **5** in 83% isolated yield (Scheme 2). The synthesis of the hydroxide-bearing **4** was next attempted from **5**.

After a reaction time of 1 h, **4** was isolated in 80% yield (Scheme 2). This reaction represents the first successful synthesis of Au-hydroxides bearing NHC ligands other than IPr. Crystals suitable for single-crystal diffraction studies were obtained by slow diffusion of pentane into a saturated THF solution of **4** (Fig. 1). As expected, **4** adopts a linear geometry, with a C1–Au–O1 angle of 180.00(1)°, a Au–C1 bond length of 1.976(8) Å and a Au–O1 bond length of 2.019(7) Å.[14] The Au–C1 bond distance is longer for the SIPr complexes than for the IPr complexes (1.935(6) Å for hydroxide **1**). This trend can also be observed in the Au–C1bond distances in the chloro complexes **2** and **6** (1.942(3) Å for IPr and 1.979(3) Å for SIPr). These differences could possibly be due to the steric bulk of the ligands. Computational studies using Samb$V$ca[15] reveal that the $\%V_{\text{Bur}}$ is greater for **4** (46.6) than for **1** (43.2).[16] On the other hand, the Au–O1 distance is significantly shorter for **4** compared to that found in **1** (2.078(6) Å).

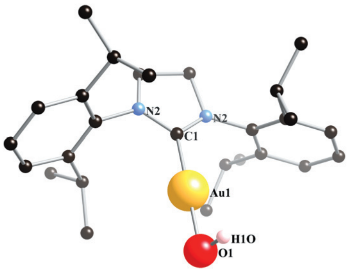
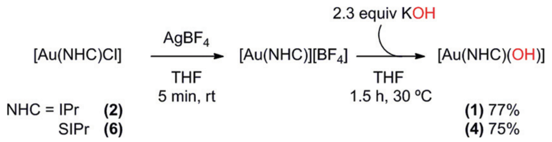


Fig. 1 Molecular representation of [Au(SIPr)(OH)] **4**. Most H atoms are omitted for clarity. Selected bond distances (Å) and angles (°) for **4**: Au1–O1 2.019(7), Au1–C1 1.976(8), C1–Au1–O1 180.00(1).

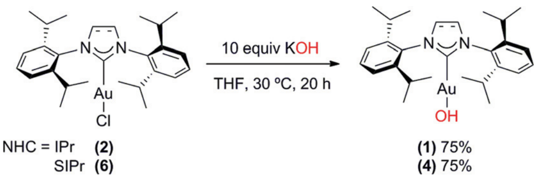


Scheme 3 One-pot synthesis of [Au(NHC)(OH)] from [Au(NHC)Cl] precursors.

Since this new synthetic route requires, initially, the synthesis and isolation of the digold complex, the development of a more straightforward procedure was investigated next. As the reaction proceeded faster and under milder conditions using a cationic species, *e.g.* **5**, a one-pot approach was devised. Starting from a chloro complex [Au(NHC)Cl], using AgBF$_4$ as chloride abstractor, the cationic gold species [Au(NHC)][BF$_4$] was generated. After filtration of the AgCl produced during the reaction, 2.3 equiv of KOH were next added. We were very pleased to observe that after stirring for 1.5 h at 30 °C, the reaction was complete and both hydroxides **1** and **4** could be isolated in good yields, 77% and 75% respectively using this procedure (Scheme 3).

One further advance had to be considered. In order to avoid the use of expensive silver salts, several chloride abstractors were screened. During the course of this study, a control reaction showed that if a larger excess of KOH was used, silver salts were unnecessary and the reaction reached completion within 20 h.

As we could perform the reaction without silver salts, using longer but still acceptable reaction times, the reaction conditions were optimized in THF, stirring for 20 h at 30 °C, affording both hydroxides, **1** and **4**, in 75% isolated yields (Scheme 4).



Scheme 4 Optimized reaction conditions.

The faster reaction times observed when the reaction is carried out through the intermediacy of the cationic gold species, suggest that the rate-determining step in the reaction is the chloride abstraction from the [Au(NHC)Cl] complex. When efficient chloride abstractors are used, *e.g.* silver salts, the hydroxide exchange is faster and complexes **1** and **4** are obtained within 2 h. Whilst in the absence of a chloride abstractor, the hydroxide exchange is slower and the reaction requires at least 20 h.

We suspect that the problem encountered with the synthesis of Au-hydroxides bearing NHC ligands other than IPr is the thermal stability of the intermediate species generated during the reaction. In the original procedure for the synthesis of hydroxide **1**, it was necessary to heat the reaction to 60 °C;[3] whilst in the present procedure, the temperature was reduced to 30 °C but requires the use of a larger amount of KOH.

In order to validate the scalability of the new excess KOH procedure, complexes **1** and **4** were synthesized on 1 g scale. Gratifyingly, the reactions reached completion within 24 h, affording gold hydroxides **1** and **4**, in 75% and 70% isolated yields, respectively.

Conclusions

A new strategy for the synthesis of Au^I-hydroxide complexes is reported and, through optimization, insights into the reaction mechanism leading to the formation of the gold hydroxides are provided. A two-step procedure starting from [Au(NHC)Cl], generating $[\{Au(NHC)\}_2(\mu\text{-}OH)][BF_4]$ and subsequent addition of KOH afforded [Au(NHC)(OH)] in good yields (80–86%) with short reaction times (1 h). This procedure enabled the isolation of the novel [Au(SIPr)(OH)]. A one-pot reaction, without isolation of a digold species, was then developed. Reaction *via* the cationic species $[Au(NHC)][BF_4]$ also allowed the formation of gold hydroxides in good yields (75–77%) and short reaction times (1.5 h). In order to avoid using expensive silver salts, [Au(NHC)(OH)] (NHC = IPr and SIPr) could be isolated in good yields by using a simpler protocol where a larger amount of KOH is employed. However, longer reaction times are required due to the inefficient chloride abstraction performed by KOH in this regime. In the end, for synthetic purposes Ockham's razor[17] prevails, *simpler is better* and only a larger excess of KOH appears to solve issues of scalability and reproducibility previously encountered.

Further studies towards the application of this procedure in the synthesis of new [Au(NHC)(OH)] complexes and investigations into the properties of these novel complexes are ongoing in our laboratories.

Acknowledgements

The ERC (Advanced Investigator Award-FUNCAT) and the EPSRC are gratefully acknowledged for support of this work. Umicore AG is acknowledged for their generous gift of auric acid. We thank Dr Sylvain Gaillard for preliminary synthetic contributions. S.P.N. is a Royal Society Wolfson Research Merit Award holder.

Notes and references

§ *Synthesis of* $[\{Au(SIPr)\}_2(\mu\text{-}OH)][BF_4]$ (**5**): $AgBF_4$ (40 mg, 204 μmol) was added to a stirred solution of [Au(SIPr)Cl] (**6**) (100 mg, 160 μmol) in dichloromethane (3 mL). The reaction mixture was stirred avoiding the presence of light at rt for 5 min and then filtered over Celite into a separating funnel containing distilled water (10 mL). The mixture was shaken for 1 min. The organic phase was collected, dried over anhydrous $MgSO_4$ and concentrated under vacuum. The resulting solid was dissolved in the minimum amount of CH_2Cl_2 (2 mL) and the product was precipitated by addition of pentane (8 mL). The precipitate was collected by filtration, affording **5** as a white powder in 83% yield ^1H NMR (400 MHz; CD_2Cl_2): δ = 7.42 (t, J = 7.8 Hz, 4H), 7.19 (d, J = 7.8 Hz, 8H), 4.01 (s, 8H), 2.88 (sept, J = 6.9 Hz, 8H), 1.28 (d, J = 6.9 Hz, 24H), 1.16 (d, J = 6.8 Hz, 24H), 0.37 (s, 1H) ppm. ^{13}C NMR (101 MHz; CD_2Cl_2): δ = 186.1, 146.9, 134.1, 130.4, 124.9, 53.93, 53.80, 29.1, 25.2, 24.1 ppm. ^{19}F NMR (376 MHz; CD_2Cl_2): δ = −154.09, −154.14 ppm. Anal. Calcd. for $C_{54}H_{77}Au_2BF_4N_4O$ (1278.95): C, 50.71; H, 6.07; N, 4.38. Found: C, 50.58; H, 6.00; N, 4.49.

Synthesis of [Au(SIPr)(OH)] (**4**): KOH (90 mg, 1.60 mmol) was added to a stirred solution of [Au(SIPr)Cl] (**6**) (100 mg, 0.16 mmol) in THF (3 mL). The reaction mixture was stirred for 24 h at 30 °C, then filtered through Celite and concentrated under vacuum. The resulting solid was dissolved in the minimum amount of THF (2 mL) and the product was precipitated by addition of pentane (8 mL). The precipitate was collected by filtration, affording **4** as a white powder in 75% yield. ^1H NMR (400 MHz; CD_2Cl_2): δ = 7.45 (t, J = 7.8 Hz, 2H), 7.28 (d, J = 7.8 Hz, 4H), 3.99 (s, 4H), 3.06 (sept, J = 6.9 Hz, 4H), 1.41 (d, J = 6.8 Hz, 12H), 1.33 (d, J = 6.9 Hz, 12H), −0.71 (br, 1H) ppm. ^{13}C NMR (101 MHz; CD_2Cl_2): δ = 193.5, 147.2, 135.0, 130.0, 124.8, 53.7, 29.2, 25.1, 24.2 ppm. Anal. Calcd for $C_{27}H_{39}AuN_2O$ (604.58): C, 53.64; H, 6.50; N, 4.63. Found: C, 53.50; H, 6.36; N, 4.48.

1 (*a*) A. S. K. Hashmi, *Chem. Rev.*, 2007, **107**, 3180–3211; (*b*) E. Jimenez-Nunez and A. M. Echavarren, *Chem. Commun.*, 2007, 333–346; (*c*) A. S. K. Hashmi and M. Rudolph, *Chem. Soc. Rev.*, 2008, **37**, 1766–1775; (*d*) E. Jiménez-Núñez and A. M. Echavarren, *Chem. Rev.*, 2008, **108**, 3326–3350; (*e*) Z. Li, C. Brouwer and C. He, *Chem. Rev.*, 2008, **108**, 3239–3265; (*f*) T. C. Boorman and I. Larrosa, *Chem. Soc. Rev.*, 2011, **40**, 1910–1925; (*g*) O. Debleds, E. Gayon, E. Vrancken and J.-M. Campagne, *Beilstein J. Org. Chem.*, 2011, **7**, 866–877; (*h*) J. J. Hirner, Y. Shi and S. A. Blum, *Acc. Chem. Res.*, 2011, **44**, 603–613; (*i*) S. Hummel and S. F. Kirsch, *Beilstein J. Org. Chem.*, 2011, **7**, 847–859; (*j*) M. Rudolph and A. S. K. Hashmi, *Chem. Commun.*, 2011, **47**, 6536–6544.

2 (*a*) N. Marion and S. P. Nolan, *Chem. Soc. Rev.*, 2008, **37**, 1776–1782; (*b*) S. P. Nolan, *Acc. Chem. Res.*, 2011, **44**, 91–100 and references cited.

3 S. Gaillard, A. M. Z. Slawin and S. P. Nolan, *Chem. Commun.*, 2010, **46**, 2742–2744.

4 S. Gaillard, C. S. J. Cazin and S. P. Nolan, *Acc. Chem. Res.*, 2012, **45**, DOI: 10.1021/ar200188f.

5 G. C. Fortman, A. Poater, J. W. Levell, S. Gaillard, A. M. Z. Slawin, I. D. W. Samuel, L. Cavallo and S. P. Nolan, *Dalton Trans.*, 2010, **39**, 10382–10390.

6 (*a*) I. I. F. Boogaerts and S. P. Nolan, *J. Am. Chem. Soc.*, 2010, **132**, 8858–8859; (*b*) S. Dupuy, F. Lazreg, A. M. Z. Slawin, C. S. J. Cazin and S. P. Nolan, *Chem. Commun.*, 2011, **47**, 5455–5457.

7 S. Gaillard, J. Bosson, R. S. Ramón, P. Nun, A. M. Z. Slawin and S. P. Nolan, *Chem.–Eur. J.*, 2010, **16**, 13729–13740.

8 (*a*) S. Gaillard, P. Nun, A. M. Z. Slawin and S. P. Nolan, *Organometallics*, 2010, **29**, 5402–5408; (*b*) P. Nun, S. Gaillard, A. M. Z. Slawin and S. P. Nolan, *Chem. Commun.*, 2010, **46**, 9113–9115; (*c*) E. Brulé, S. Gaillard, M.-N. Rager, T. Roisnel, V. Guérineau, S. P. Nolan and C. M. Thomas, *Organometallics*, 2011, **30**, 2650–2653; (*d*) D. Konkolewicz, S. Gaillard, A. G. West, Y. Y. Cheng, A. Gray-Weale, T. W. Schmidt, S. P. Nolan and S. Perrier, *Organometallics*, 2011, **30**, 1315–1318; (*e*) P. Nun, S. Dupuy, S. Gaillard, A. Poater, L. Cavallo and S. P. Nolan, *Catal. Sci. Technol.*, 2011, **1**, 58–61; (*f*) P. Nun, S. Gaillard, A. Poater, L. Cavallo and S. P. Nolan, *Org. Biomol. Chem.*, 2011, **9**, 101–104; (*g*) S. R. Patrick, I. I. F. Boogaerts, S. Gaillard, A. M. Z. Slawin and S. P. Nolan, *Beilstein J. Org. Chem.*, 2011, **7**, 892–896.

9 For the first report on the synthesis and use of IPr as supporting ligand in catalysis, see: J. Huang and S. P. Nolan, *J. Am. Chem. Soc.*, 1999, **121**, 9889–9890.

10 R. S. Ramón, S. Gaillard, A. Poater, L. Cavallo, A. M. Z. Slawin and S. P. Nolan, *Chem.–Eur. J.*, 2011, **17**, 1238–1246.

11 (*a*) R. S. Ramón, S. Gaillard, A. M. Z. Slawin, A. Porta, A. D'Alfonso, G. Zanoni and S. P. Nolan, *Organometallics*, 2010, **29**, 3665–3668; (*b*) V. Merlini, S. Gaillard, A. Porta, G. Zanoni, G. Vidari and S. P. Nolan, *Tetrahedron Lett.*, 2011, **52**, 1124–1127.

12 In order to avoid formation of chloro species **2** by traces of HCl in chlorinated solvents, THF was used.

13 The reactions were carried out at 30 °C rather than at rt to ensure reproducibility.

14 As the H of the OH is disordered, no O–H length is given.

15 A. Poater, B. Cosenza, A. Correa, S. Giudice, F. Ragone, V. Scarano and L. Cavallo, *Eur. J. Inorg. Chem.*, 2009, 1759–1766.

16 Parameters used for SambV_{ca} calculations: (a) 3.50 Å was selected as the value for the sphere radius, (b) 2.00 Å was considered as distances for the metal–ligand bond, (c) usually irrelevant in crystallography, hydrogen atoms were omitted, and (d) Bondi radii scaled by 1.17 were used.

17 Ockham's razor (*lex parsimoniae* or the law of parsimony) states that "entities must not be multiplied beyond necessity" (*entia non-sunt multiplicanda praeter necessitatem*). We find the present synthetic study to be a good representation of this principle.