



CrossMark
click for updates

Cite this: *Chem. Sci.*, 2016, 7, 89

Dual gold/photoredox-catalyzed C(sp)–H arylation of terminal alkynes with diazonium salts†

Adrian Tlahuext-Aca,^{‡,ab} Matthew N. Hopkinson,^{‡,a} Basudev Sahoo^{ab} and Frank Glorius^{*a}

The arylation of alkyl and aromatic terminal alkynes by a dual gold/photoredox catalytic system is described. Using aryldiazonium salts as readily available aryl sources, a range of diversely-functionalized arylalkynes could be synthesized under mild, base-free reaction conditions using visible light from simple household sources or even sunlight. This process, which exhibits a broad scope and functional group tolerance, expands the range of transformations amenable to dual gold/photoredox catalysis to those involving C–H bond functionalization and demonstrates the potential of this concept to access Au^I/Au^{III} redox chemistry under mild, redox-neutral conditions.

Received 16th July 2015
Accepted 7th October 2015

DOI: 10.1039/c5sc02583d

www.rsc.org/chemicalscience

Introduction

Homogeneous gold catalysis has received significant attention in the last two decades. Due to their carbophilic π -acidity, Au^I and Au^{III} complexes catalyze the addition of a variety of oxygen-, nitrogen-, carbon-, and sulfur-based nucleophiles to unsaturated molecules, such as alkynes, allenes and alkenes, giving rapid and efficient access to complex molecular architectures.¹ A common feature regarding the nature of the catalytically active Au species is that it does not easily undergo changes in oxidation state during the course of these reactions. However, there has been significant recent interest in developing Au^I/Au^{III} catalytic processes with the aim of expanding the repertoire of gold-mediated processes, mimicking conventional Mⁿ/Mⁿ⁺² redox cycles of the type commonly invoked in catalysis by other late transition metals.² Nevertheless, in contrast to its isoelectronic counterpart Pd⁰, the oxidation of Au^I generally requires the use of strong oxidative conditions due to the high redox potential of the Au^I/Au^{III} redox couple ($E_0 = 1.41$ V).³ A common strategy to access catalytically active Au^{III} species *in situ* from Au^I complexes has been to use strong external oxidants, such as Selectfluor®, *t*BuOOH, or hypervalent iodine reagents. Applying this concept, a range of oxidative homo- and heterocoupling reactions have been developed over the last few years where the oxidative coupling event follows a conventional gold-mediated

nucleophilic addition reaction to a C–C multiple bond, circumventing protodeauration and giving efficient access to difunctionalized products (Scheme 1a). This strategy has also been successfully applied in a selection of coupling reactions of unfunctionalized arenes and alkynes, exploiting the well-established ability of gold to activate C(sp²)–H or C(sp)–H bonds (Scheme 1b).⁴

Despite the success of these approaches, the use of strong external oxidants, typically in super-stoichiometric amounts, inevitably reduces their attractiveness with regards to functional group tolerance and cost, while most examples are also conducted at high reaction temperatures. With the goal of developing milder gold-catalyzed coupling reactions that do not require external oxidants, our group recently described the use of a dual gold/photoredox catalysis strategy to access Au^I/Au^{III} redox cycles.^{5,6} Using this concept, we have developed



Scheme 1 Gold-catalyzed C–C and C–X bond-forming coupling reactions proposed to proceed via Au^I/Au^{III} redox cycles.

^aOrganisch-Chemisches Institut, Westfälische Wilhelms-Universität Münster, Corrensstraße 40, 48149 Münster, Germany. E-mail: glorius@uni-muenster.de

^bNRW Graduate School of Chemistry, Westfälische Wilhelms-Universität Münster, Wilhelm-Klemm-Strasse 10, 48149 Münster, Germany

† Electronic supplementary information (ESI) available: General experimental details, full optimization table, kinetic profile, experimental procedures and characterization data of products, copies of NMR spectra. See DOI: 10.1039/c5sc02583d

‡ These authors contributed equally.



intramolecular aminoarylation and both intra^{5a} and intermolecular^{5b} oxyarylation reactions of alkenes to afford arylated heterocycles and β -aryl ethers employing aryldiazonium or diaryliodonium salts as general arylating agents (Scheme 1c). This dual catalytic system, which has since been further exploited by the Toste group in an impressive arylative ring expansion^{7a} and C–P bond-forming cross-coupling,^{7b} operates under mild and overall redox neutral conditions and uses abundant visible light as an energy source. Building on these studies, we sought to expand the scope of dual gold/photoredox catalysis onto new classes of transformations, exploiting different aspects of the rich chemistry of gold. In this regard, we turned our attention to the development of novel visible light-mediated cross-coupling reactions involving gold-catalyzed C–H bond activation and identified the well-established ability of gold(i) to activate the C(sp)³–H bond of terminal alkynes as a promising avenue of investigation. Arylation of the resulting alkynylgold complexes would deliver cross-coupled arylalkyne products in a dual gold and photoredox-catalyzed analogue of the widely-employed Sonogashira–Hagihara reaction.^{8,9} As demonstrated below, this process benefits from mild conditions (room temperature, household light bulb) and broad functional group tolerance while making use of readily-available aryldiazonium salts as the arene coupling partner. Furthermore, by exploiting a non-conventional stepwise oxidation process of Au^I complexes into active Au^{III} species by means of organic radicals generated under photoredox catalysis, we have developed a very fast arylating system that proceeds under base-free conditions.¹⁰

Results and discussion

In a preliminary experiment, *p*-tolylacetylene (**1a**) was reacted in the presence of benzenediazonium tetrafluoroborate (**2a**) under visible light irradiation from a simple household desk lamp fitted with a 23 W fluorescent light bulb (CFL). Upon treatment with 10 and 2.5 mol% of Ph₃PAuCl and [Ru(bpy)₃](PF₆)₂, respectively, in degassed methanol for 2 h at room temperature, we were pleased to observe that the cross-coupled product **3aa** was formed in 46% yield (entry 1). Following a short screen, (see the ESI† for details of additional experiments), DMF was identified as the optimum solvent for this transformation (entry 2). A range of different Au^I catalysts bearing various ligands were then evaluated (entries 3–7). Interestingly, the gold(i) chloride complex possessing the comparatively electron-rich phosphine ((*p*-MeO)C₆H₄)₃P led to the highest yield of **3aa** (83%), while the trialkylphosphine Cy₃P was also tolerated (entry 4). This trend might be related to the stabilization of the Au^{III} center by these strongly donating ligands during the Au^I/Au^{III} redox cycle. The combination of the Au^I complex ((*p*-MeO)C₆H₄)₃PAuCl and the photoredox catalyst [Ru(bpy)₃](PF₆)₂ turned out to be both a highly selective and active C(sp)³–H arylating system, as **3aa** could be isolated in 80% yield using very low loadings of [Ru(bpy)₃](PF₆)₂ (0.5 mol%) after a reaction time of only 1 hour and without the formation of the diyne homocoupling product of **1a** (entry 8).¹¹ Furthermore, this system does not require the addition of an external base and proceeds under acidic



Scheme 2 Dual Au/photoredox-catalyzed arylation of different alkynes. General conditions: alkyne (**1a–m**, 0.30 mmol), **2b** (1.2 mmol), [Ru(bpy)₃](PF₆)₂ (0.5 mol%), ((*p*-MeO)C₆H₄)₃PAuCl (10 mol%) and degassed DMF (3.0 mL). Isolated yields.

conditions. Interestingly, the reaction also operated efficiently using visible light from a variety of different sources. Under both blue LED (5 W, $\lambda_{\text{max}} = 465$ nm) and even sunlight irradiation, the formation of the cross coupled product **3aa** was

Table 1 Reaction optimization^a

Entry	Au(I) complex	Photocatalyst	Yield ^b (%)
1 ^c	Ph ₃ PAuCl	[Ru(bpy) ₃](PF ₆) ₂	46
2	Ph ₃ PAuCl	[Ru(bpy) ₃](PF ₆) ₂	78
3	((<i>p</i> -MeO)C ₆ H ₄) ₃ PAuCl	[Ru(bpy) ₃](PF ₆) ₂	83
4	Cy ₃ PAuCl	[Ru(bpy) ₃](PF ₆) ₂	72
5	XPhosAuCl	[Ru(bpy) ₃](PF ₆) ₂	—
6	(PhO) ₃ PAuCl	[Ru(bpy) ₃](PF ₆) ₂	—
7	IPrAuCl	[Ru(bpy) ₃](PF ₆) ₂	—
8 ^d	((<i>p</i> -MeO)C ₆ H ₄) ₃ PAuCl	[Ru(bpy) ₃](PF ₆) ₂	83 (80)
9 ^e	((<i>p</i> -MeO)C ₆ H ₄) ₃ PAuCl	[Ru(bpy) ₃](PF ₆) ₂	80
10 ^f	((<i>p</i> -MeO)C ₆ H ₄) ₃ PAuCl	[Ru(bpy) ₃](PF ₆) ₂	71
11 ^g	((<i>p</i> -MeO)C ₆ H ₄) ₃ PAuCl	[Ru(bpy) ₃](PF ₆) ₂	60
12 ^h	((<i>p</i> -MeO)C ₆ H ₄) ₃ PAuCl	[Ru(bpy) ₃](PF ₆) ₂	82
13 ⁱ	((<i>p</i> -MeO)C ₆ H ₄) ₃ PAuCl	[Ir(ppy) ₂ (dtbbpy)]PF ₆	Trace
14	((<i>p</i> -MeO)C ₆ H ₄) ₃ PAuCl	Eosin Y	—
15	((<i>p</i> -MeO)C ₆ H ₄) ₃ PAuCl	Fluorescein	—

^a General conditions: **1a** (0.10 mmol), **2a** (0.40 mmol), photocatalyst (2.5 mol%), gold complex (10 mol%) and degassed DMF (1.0 mL). ^b NMR yields using CH₂Br₂ as internal standard. Isolated yield in parentheses. ^c Degassed methanol (1.0 mL). ^d [Ru(bpy)₃](PF₆)₂ (0.5 mol%), 1 h. ^e [Ru(bpy)₃](PF₆)₂ (0.5 mol%), 5 W blue LEDs, 1 h. ^f [Ru(bpy)₃](PF₆)₂ (0.5 mol%), sunlight, 8 h. ^g [Ru(bpy)₃](PF₆)₂ (0.5 mol%), air, 1 h. ^h [Ru(bpy)₃](PF₆)₂ (2.5 mol%), air, 1 h. ⁱ With Ph₂IBF₄ (0.40 mmol), [Ir(ppy)₂(dtbbpy)]PF₆ (5 mol%). See the ESI for further details. ppy = 2-phenylpyridine, dtbbpy = 4,4'-di-*tert*-butyl-2,2'-bipyridine, XPhos = 2-dicyclohexylphosphino-2',4',6'-triisopropylbiphenyl, IPr = 1,3-bis(2,6-diisopropylphenyl)-imidazol-2-ylidene.





Scheme 5 Mechanistic proposal.

Overall, this two-step protocol is complementary to stepwise palladium-catalyzed coupling sequences, making use of readily-available aryldiazonium salts rather than dihalogenated aryl iodide precursors (Scheme 4).

In accordance with previous studies on dual Au/photoredox catalysis,^{5,7} we envisage a mechanism involving a photoredox-induced homogeneous Au^I/Au^{III} redox cycle (Scheme 5).¹³ Upon irradiation with visible light, photoexcitation of the [Ru(bpy)₃]²⁺ photocatalyst takes place to generate the excited form ^{*}[Ru(bpy)₃]²⁺ which then undergoes single electron transfer (SET) with one equivalent of the aryldiazonium salt to deliver an aryl radical and the oxidized species [Ru(bpy)₃]³⁺.¹⁴ The photo-generated aryl radical then adds to the Au^I catalyst to give the Au^{II} species A.¹⁵ Interestingly, quantum yield measurements at 450 nm by chemical actinometry gave a value of 3.6, reflecting the very important contribution of radical chain processes in this dual catalytic system.¹⁶ Therefore, we propose that a second SET process between the open-shell species A with another equivalent of the aryldiazonium salt mainly contributes to the formation of the electrophilic cationic Au^{III} intermediate B. Nevertheless, regeneration of the oxidized [Ru(bpy)₃]³⁺ to the [Ru(bpy)₃]²⁺ photocatalyst is still feasible by reaction with A. The cationic intermediate B is expected to be an excellent π-Lewis acid and coordinates the alkyne substrate, activating it towards the formation of the σ-bonded alkynyl-Au^{III} complex C upon deprotonation. Intermediate C finally undergoes reductive elimination,¹⁷ regenerating the Au^I catalyst and delivering the cross-coupled product.

Conclusions

In conclusion, we have developed an efficient dual gold/photoredox catalysis methodology for the arylation of terminal alkynes using readily-available aryldiazonium salts. This overall redox neutral cross-coupling process shows broad functional group tolerance, operates at room temperature and is mediated by abundant visible light from a household light bulb or even

sunlight. In addition, the base-free nature of the reaction and tolerance of halogenated substrates may be beneficial in the design of cross-coupling sequences. This reaction represents the first application of dual gold/photoredox catalysis for the activation of C–H bonds and further demonstrates the potential of this methodology to access Au^I/Au^{III} redox cycles under mild conditions without the need for external oxidants.

Acknowledgements

We thank T. Pillath for experimental assistance. Generous financial support by the NRW Graduate School of Chemistry (A. T. A. and B. S.), the Alexander von Humboldt Foundation (M. N. H.) and the Deutsche Forschungsgemeinschaft (Leibniz Award) are gratefully acknowledged.

Notes and references

- Selected reviews on homogeneous gold catalysis: (a) A. S. K. Hashmi, *Angew. Chem., Int. Ed.*, 2005, **44**, 6990; (b) A. Fürstner and P. W. Davies, *Angew. Chem., Int. Ed.*, 2007, **46**, 3410; (c) D. J. Gorin and F. D. Toste, *Nature*, 2007, **446**, 395; (d) A. Fürstner, *Chem. Soc. Rev.*, 2009, **38**, 3208; (e) N. D. Shapiro and F. D. Toste, *Synlett*, 2010, 675; (f) A. S. K. Hashmi, *Angew. Chem., Int. Ed.*, 2010, **49**, 5232; (g) N. Krause and C. Winter, *Chem. Rev.*, 2011, **111**, 1994; (h) M. Rudolph and A. S. K. Hashmi, *Chem. Commun.*, 2011, 47, 6536; (i) M. Bandani, *Chem. Soc. Rev.*, 2011, **40**, 1358; (j) L.-P. Liu and G. B. Hammond, *Chem. Soc. Rev.*, 2012, **41**, 3129; (k) M. Rudolph and A. S. K. Hashmi, *Chem. Soc. Rev.*, 2012, **41**, 2448; (l) C. Obradors and A. M. Echavarren, *Chem. Commun.*, 2014, **50**, 16; (m) A. Fürstner, *Acc. Chem. Res.*, 2014, **47**, 925; (n) R. Dorel and A. M. Echavarren, *Chem. Rev.*, 2015, **115**, 9028.
- Selected reviews: (a) M. N. Hopkinson, A. D. Gee and V. Gouverneur, *Chem.-Eur. J.*, 2011, **17**, 8248; (b) H. A. Wegner and M. Auzias, *Angew. Chem., Int. Ed.*, 2011, **50**, 8236; (c) K. M. Eagle, T.-S. Mei, X. Wang and J.-Q. Yu, *Angew. Chem., Int. Ed.*, 2011, **50**, 1478.
- (a) S. G. Bratsch, *J. Chem. Phys. Ref. Data*, 1989, **18**, 1; Recently a few impressive examples of oxidative addition of C–Br/I and C–C bonds onto Au^I have been reported: (b) J. Guenther, S. Mallet-Ladeira, L. Estevez, K. Miqueu, A. Amgoune and D. Bourissou, *J. Am. Chem. Soc.*, 2014, **136**, 1778; (c) M. D. Levin and F. D. Toste, *Angew. Chem., Int. Ed.*, 2014, **53**, 6211; (d) M. Joost, A. Zeineddine, L. Estévez, S. Mallet-Ladeira, K. Miqueu, A. Amgoune and D. Bourissou, *J. Am. Chem. Soc.*, 2014, **136**, 14654; (e) C.-Y. Wu, T. Horibe, C. B. Jacobsen and F. D. Toste, *Nature*, 2015, **517**, 449; (f) M. Joost, L. Estévez, K. Miqueu, A. Amgoune and D. Bourissou, *Angew. Chem., Int. Ed.*, 2015, **54**, 5236.
- T. C. Boorman and I. Larrosa, *Chem. Soc. Rev.*, 2011, **40**, 1910.
- (a) B. Sahoo, M. N. Hopkinson and F. Glorius, *J. Am. Chem. Soc.*, 2013, **135**, 5505; (b) M. N. Hopkinson, B. Sahoo and F. Glorius, *Adv. Synth. Catal.*, 2014, **356**, 2794.



- 6 Selected reviews on visible light photoredox catalysis: (a) K. Zeitler, *Angew. Chem., Int. Ed.*, 2009, **48**, 9785; (b) T. P. Yoon, M. A. Ischay and J. Du, *Nat. Chem.*, 2010, **2**, 527; (c) F. Teplý, *Collect. Czech. Chem. Commun.*, 2011, **76**, 859; (d) J. M. R. Narayanam and C. R. J. Stephenson, *Chem. Soc. Rev.*, 2011, **40**, 102; (e) J. Xuan and W.-J. Xiao, *Angew. Chem., Int. Ed.*, 2012, **51**, 6828; (f) L. Shi and W. Xia, *Chem. Soc. Rev.*, 2012, **41**, 7687; (g) S. Fukuzumi and K. Ohkubo, *Chem. Sci.*, 2013, **4**, 561; (h) Y. Xi, H. Yi and A. Lei, *Org. Biomol. Chem.*, 2013, **11**, 2387; (i) C. K. Prier, D. A. Rankic and D. W. C. MacMillan, *Chem. Rev.*, 2013, **113**, 5322; (j) J. Xuan, L.-Q. Lu, J.-R. Chen and W.-J. Xiao, *Eur. J. Org. Chem.*, 2013, 6755; (k) M. Reckenthäler and A. G. Griesbeck, *Adv. Synth. Catal.*, 2013, **355**, 2727; (l) D. M. Schultz and T. P. Yoon, *Science*, 2014, **343**, 1239176; (m) T. Koike and M. Akita, *Top. Catal.*, 2014, **57**, 967; (n) D. A. Nicewicz and T. M. Nguyen, *ACS Catal.*, 2014, **4**, 355; (o) M. N. Hopkinson, B. Sahoo, J.-L. Li and F. Glorius, *Chem.-Eur. J.*, 2014, **20**, 3874; (p) E. Meggers, *Chem. Commun.*, 2015, **51**, 3290.
- 7 (a) X.-Z. Shu, M. Zhang, Y. He, H. Frei and F. D. Toste, *J. Am. Chem. Soc.*, 2014, **136**, 5844; (b) Y. He, H. Wu and F. D. Toste, *Chem. Sci.*, 2015, **6**, 1194.
- 8 Recent review on the Sonogashira–Hagihara reaction: (a) R. Chinchilla and C. Nájera, *Chem. Soc. Rev.*, 2011, **40**, 5084; examples of Pd-catalyzed alkyne arylation with aryldiazonium salts: (b) G. Fabrizi, A. Goggiamani, A. Sferazza and S. Cacchi, *Angew. Chem., Int. Ed.*, 2010, **49**, 4067; (c) B. Panda and T. K. Sarkar, *Chem. Commun.*, 2010, **46**, 3131; (d) X.-F. Fu, H. Neumann and M. Beller, *Chem. Commun.*, 2011, **47**, 7959; (e) M. Barbero, S. Cadamuro and S. Dughera, *Eur. J. Org. Chem.*, 2014, 598.
- 9 While a few examples of gold-catalyzed Sonogashira–Hagihara reactions with aryl halides have been reported, the mechanism of these processes has been the subject of debate. Trace palladium impurities and heterogeneous gold nanoparticles have both been implicated in these reactions: (a) C. González-Arellano, A. Abad, A. Corma, H. García, M. Iglesias and F. Sánchez, *Angew. Chem., Int. Ed.*, 2007, **46**, 1536; (b) P. Li, L. Wang, M. Wang and F. You, *Eur. J. Org. Chem.*, 2008, 5946; (c) C. González-Arellano, A. Corma, M. Iglesias and F. Sánchez, *Eur. J. Inorg. Chem.*, 2008, 1107; (d) T. Lauterbach, M. Livendahl, A. Rosellón, P. Espinet and A. M. Echavarren, *Org. Lett.*, 2010, **12**, 3006; (e) G. Kyriakou, S. K. Beaumont, S. M. Humphrey, C. Antonetti and R. M. Lambert, *ChemCatChem*, 2010, **2**, 1444; (f) A. Corma, R. Juárez, M. Boronat, F. Sánchez, M. Iglesias and H. García, *Chem. Commun.*, 2011, **47**, 1446; (g) M. Livendahl, P. Espinet and A. M. Echavarren, *Platinum Met. Rev.*, 2011, **55**, 212; (h) P. S. D. Robinson, G. N. Khairallah, G. da Silva, H. Lioe and R. A. J. O'Hair, *Angew. Chem., Int. Ed.*, 2012, **51**, 3812; examples of gold-catalyzed alkyne arylation with external oxidants: (i) T. de Haro and C. Nevado, *J. Am. Chem. Soc.*, 2010, **132**, 1512; (j) M. N. Hopkinson, J. E. Ross, G. T. Giuffredi, A. D. Gee and V. Gouverneur, *Org. Lett.*, 2010, **12**, 4904; (k) D. Qian and J. Zhang, *Beilstein J. Org. Chem.*, 2011, **7**, 808; (l) Y. Ma, S. Zhang, S. Yang, F. Song and J. You, *Angew. Chem., Int. Ed.*, 2014, **53**, 7870; (m) H. Peng, Y. Xi, N. Ronaghi, B. Dong, N. G. Akhmedov and X. Shi, *J. Am. Chem. Soc.*, 2014, **136**, 13174; review on gold-catalyzed alkyne arylation including examples not involving C(sp)³–H bond activation: (n) J. P. Brand, Y. Li and J. Waser, *Isr. J. Chem.*, 2013, **53**, 901.
- 10 During the preparation of this manuscript, Shi and co-workers reported a ligand assisted gold-catalyzed coupling of terminal alkynes with aryldiazonium salts. This catalytic system does not involve photoredox activation and explores a ligand-assisted two electron oxidation process of the Au(I) complex under basic conditions, thus proceeding by a different mechanism: R. Cai, M. Lu, E. Y. Aguilera, Y. Xi, N. G. Akhmedov, J. L. Petersen, H. Chen and X. Shi, *Angew. Chem., Int. Ed.*, 2015, **54**, 8772.
- 11 Control experiments without the AuI catalyst, photocatalyst or visible light gave trace amounts or no product formation. Careful analysis of reaction mixtures by GC-MS showed no diyne homocoupling product formation (see the ESI† for further information).
- 12 (a) Y. Miao, A. Dupé, C. Bruneau and C. Fischmeister, *Eur. J. Org. Chem.*, 2014, 5071; (b) X. Shen, D. M. Ho and R. A. Pascal Jr, *J. Am. Chem. Soc.*, 2004, **126**, 5798.
- 13 The kinetic profile of the reaction did not exhibit an induction period, implying that heterogeneous gold nanoparticles are not responsible for the observed reactivity (see the ESI† for more details, see also ref. 9f–h for a discussion of heterogeneous gold-catalyzed coupling reactions).
- 14 Review on the photoredox activation of diazonium salts: D. P. Hari and B. König, *Angew. Chem., Int. Ed.*, 2013, **52**, 4734.
- 15 Seminal study on the trapping of carbon-based radicals by gold complexes: (a) C. Aprile, M. Boronat, B. Ferrer, A. Corma and H. García, *J. Am. Chem. Soc.*, 2006, **128**, 8388; recent report on the oxidation of gold(I) by the CF₃ radical: (b) M. S. Winston, W. J. Wolf and F. D. Toste, *J. Am. Chem. Soc.*, 2014, **136**, 7777.
- 16 For interesting discussions on the prevalence of radical chain processes in photoredox catalysis see: (a) M. Majek, F. Filace and A. J. von Wangelin, *Beilstein J. Org. Chem.*, 2014, **10**, 981; (b) M. A. Cismesia and T. P. Yoon, *Chem. Sci.*, 2015, **6**, 5426. For quantum yield measurements see the ESI.†
- 17 Report on reductive elimination from these complexes: Y. Fuchita, Y. Utsunomiya and M. Yasutake, *J. Chem. Soc., Dalton Trans.*, 2001, 2330.

