Dalton Transactions

Accepted Manuscript

ROYAL SOCIETY OF CHEMISTRY

www.rsc.org/dalton

Cyclometallated gold(III) aryl-pyridine complexes as efficient catalysts for three-component synthesis of substituted oxazoles†

Henrik von Wachenfeldt, Alexey V. Polukeev, Nagarajan Loganathan, Filip Paulsen, Philipp Röse, Marion Garreau, Ola F. Wendt, and Daniel Strand*

Centre for Analysis and Synthesis, Department of Chemistry, Lund University, Box 124, 221 00 Lund, Sweden.

Keywords: Gold(III) catalysis; heterocycle synthesis; multicomponent reactions

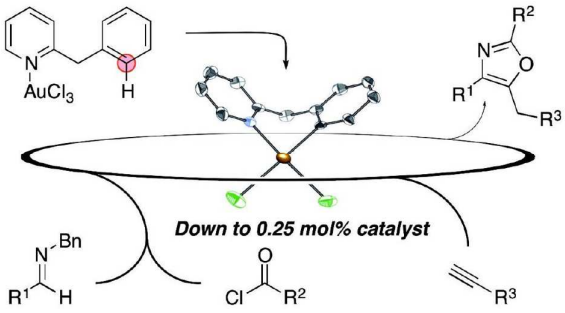
* *Corresponding author*

E-mail: daniel.strand@chem.lu.se

ABSTRACT

Cyclometallated aryl-pyridine gold (III) complexes are shown to be efficient catalysts for the multicomponent reaction between *N*-benzyl imines, alkynes, and acyl chlorides to form trisubstituted oxazoles. The reaction typically proceeds in good yields (up to over 80%) and short reaction times (~15 minutes). The high stability of the investigated cyclometallated catalysts enables a retained efficiency for this reaction in terms of rate and yield using as little as 0.5 mol % catalyst, a reduction by an order of magnitude compared to previously used Au(III)–salen complexes. An attractive feature of the present catalytic system is that active catalysts can be formed from simple pre-catalysts under the reaction conditions. Both cyclometallated and non-cyclometallated complexes were characterized in the solid state by single crystal X-ray diffraction.

TOC GRAPHIC



TOC TEXT

Cyclometallated gold(III) complexes efficiently catalyze the multicomponent reaction between imines, alkynes, and acyl chlorides to form trisubstituted oxazoles.

INTRODUCTION.

Gold catalysis has been the subject of a growing interest over the past two decades. For applications in homogenous catalysis, these efforts have been dominated by reports relying on Au(I).[1] Studies on Au(III) catalysis are more sparse and have primarily focused on the application of simple salts such as $AuCl_3$, and $AuBr_3$.[2] In more recent contributions, also Au(III) complexes with organic ligands such as salen,[3] *N*-heterocyclic carbenes,[4] phosphines,[5] picolinate,[6] and tethered aryl-pyridines[7,8] have been investigated. The role of the ligands in such systems however remains underexplored and it is often unclear whether the ligated system is the actual catalyst or if it primarily serves a precursor for more active species formed under the reaction conditions.[9] To this end, the straightforward access to structural variants of aryl-pyridine ligands constitutes an attractive entry to tuning the catalytic properties of cyclometallated Au(III) salts for use in carbon-carbon bond forming reactions such as A^3 couplings between alkynes, aldehydes and amines,[10] and multicomponent processes to form aromatic heterocycles.[11,12]

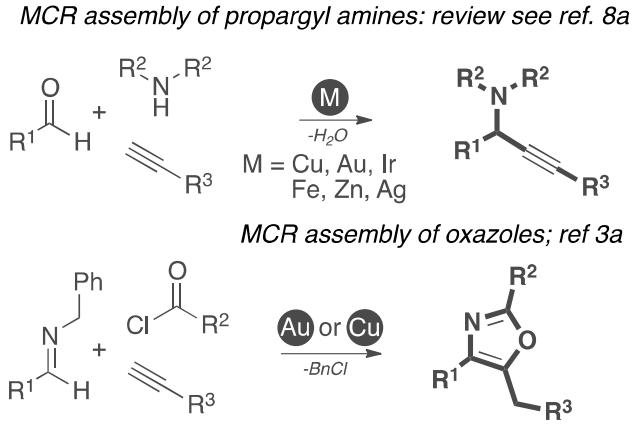


Figure 1. Three-component reactions to form propargyl amines or oxazoles under Au^{III} catalysis

In particular, the previously demonstrated efficiency of cyclometallated 2-benzylpyridine-(bnpy)$AuCl_2$ **3** in the A^3 coupling[10d] drew our attention as variations on this theme would be of value also in the context of our recently reported gold catalyzed synthesis of tri-substituted oxazoles from imines, alkynes and acyl chlorides.[3] Hence, herein we present an investigation

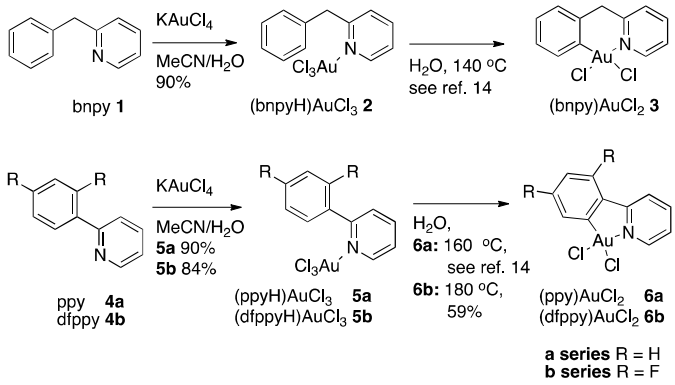
of a series of cyclometallated Au(III) complexes and their non-cyclometallated precursors as catalysts for this transformation. Compared to the previously used *N*,*N*'-ethylenebis(salicylimine)-(salen) $AuPF_6$ or $AuCl_3$, the more stable cyclometallated complexes (*i.e.* (bnpy)$AuCl_2$ **3**) enabled a reduction of the catalyst loading by a factor of ten with retained high yields and short reaction times for a number of substrate combinations. An additional attractive feature of this system is that a simple pre-catalyst, the non-cyclometallated precursor of (bnpy)$AuCl_2$ **3**, (bnpyH)$AuCl_3$ **2**, readily formed in minutes from commercially available $KAuCl_4$ and 2-benzylpyridine (**1**), can be used without significant loss of efficiency, presumably as cyclometallation occurs, at least in part, under the reaction conditions. A series of aryl-pyridine complexes with varying tether lengths and electronic properties of the aryl moiety were also investigated and gave similar results in terms of yield; qualitatively a methylene bridge between the aryl and pyridyl moieties of the ligand was beneficial for catalysis, and electron-withdrawing substituents on the aryl moiety gave a marginally reduced efficiency compared to using 2-phenylpyridine (**4a**) as ligand.

RESULTS AND DISCUSSION

Synthesis and characterisation of cyclometallated gold catalysts. A series of Au(III) complexes were selected for investigation as catalysts and synthesized as shown in Scheme 1. The previously known L$AuCl_3$ complexes (bnpyH)$AuCl_3$ **2** and 2-phenylpyridine- (ppyH) $AuCl_3$ **5a** as well as a new complex, 2-(2,4-difluorophenyl)pyridine-(dfppyH) $AuCl_3$ **5b** were all prepared from $KAuCl_4$ and the respective pyridine ligands in mixtures of MeCN and H_2O (Scheme 1) using a modification of the literature procedure for the synthesis of **2**.[13] Complexes **2** and **5a** were subsequently cyclometallated in water using microwave heating as reported by Shaw *et al.*[14] to give the known complexes (bnpy)$AuCl_2$ **3** and (ppy)$AuCl_2$ **6a** respectively. Pleasingly, this method could also be extended to cyclometallation of **5b** to give the known (dfppy)$AuCl_2$ **6b**. Compared to the previously described transmetallation procedure for the synthesis of this complex,[15] the present procedure provided a slightly higher yield conveniently avoiding toxic mercury salts.

Mechanistically, we interpret the cyclometallation processes for this class of compounds as initiated by a nucleophilic attack of the aryl moiety on the electron deficient gold center, similar to that seen in electrophilic aromatic substitution reactions, followed by an re-aromatization of the ring with an overall loss of HCl. This is supported by a recent contribution from the Wendt and co-workers wherein naphthylpyridine-Au(III) salts were

shown to exclusively cyclometalate in the more nucleophilic naphthyl 8-position rather than in the 2-position;[16] a complete reversal in selectivity compared with for instance Pd(II) mediated C-H activation of naphthylpyridine.[17]



Scheme 1. Synthesis of Au-pyridine complexes **2**, **3**, **5a/b**, and **6a/b**.

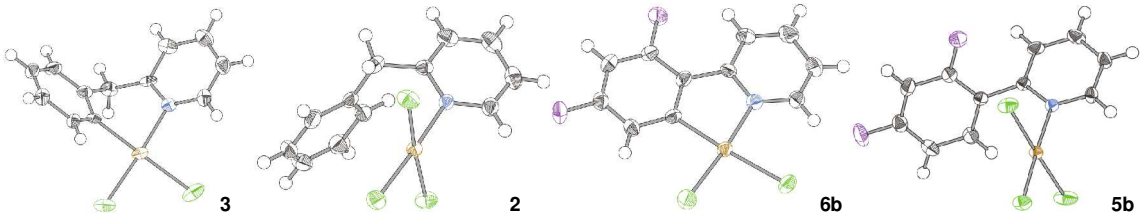
The ^{1}H NMR spectrum of (dfppyH)AuCl$_3$ **5b** reveals the expected seven resonances with well-resolved long-range couplings; the resonance from H5 of the pyridine ring is shifted downfield (9.39 ppm); consistent with coordination of nitrogen to AuCl$_3$. In the ^{13}C{^{1}H} NMR spectrum, all carbons of the phenyl ring are split by the two non-equivalent fluorine atoms.

Single crystal XRD structures of (bnpy)AuCl$_2$ **3**, (bnpyH)AuCl$_3$ **2**, (dfppy)AuCl$_2$ **6b** and (dfppyH)AuCl$_3$ **5b** have not been described previously.[18] Pleasingly, single crystals of these compounds suitable for XRD analysis could be grown by slow evaporation of acetonitrile (**3**, **2**, and **6b**) or acetone (**5b**) solutions. The respective molecular structures are given together with crystallographic data in Table 2.

All structures display distorted square-planar geometries with the expected cyclometallation seen in (bnpy)AuCl$_2$ **3** and (dfppy)AuCl$_2$ **6b**. In the LAuCl$_3$ crystals, the coordinated pyridine is almost perpendicular to the coordination plane. In the cyclometallated complex (bnpy)AuCl$_2$ **3**, the six-membered metallacycle forces the ligand out of the coordination plane with a highly puckered conformation as a result. On the other hand, the constraints imposed by the five member metallacycle in (dfppy)AuCl$_2$ **6b** result in the ligand adapting a co-planar orientation with the coordination plane giving an almost perfectly planar molecule similarly to what was found in the structure of the parent phenylpyridine complex **6a**.[18b] Compounds **6a** and **6b** are thus set-up for a strong π-interaction between ligand and metal, which is reflected in the substantially shorter Au–N and Au–C distances in these structures compared to the corresponding distances in (bnpy)AuCl$_2$ **3** (*cf.* Table 1 and ref 18b). The planarity of

(dfppy)$AuCl_2$ **6b** also forces the C–Au–N angle to below 90° with an increase of the corresponding Cl–Au–Cl angle as a result, whereas in (bnpy)$AuCl_2$ **3** the bond angles around gold are closer to the ideal.

Table 2. Crystal data and refinement results for (bnpy)$AuCl_2$ **3**, (bnpyH)$AuCl_3$ **2**, (dfppy)$AuCl_2$ **6b,** and (dfppyH)$AuCl_3$ **5b**



Compound	*(bnpy)$AuCl_2$* **3**	*(bnpyH)$AuCl_3$* **2**	*(dfppy)$AuCl_2$* **6b**	*(dfppyH)$AuCl_3$* **5b**
Crystal Data				
Chemical formula	$C_{12}H_{10}AuCl_2N$	$C_{12}H_{11}AuCl_3N$	$C_{11}H_6AuCl_2F_2N$	$C_{11}H_7AuCl_3F_2N$
M_r	436.08	472.53	458.03	494.49
Crystal system, space group	Monoclinic, $P2_1/n$	Triclinic, P-1	Monoclinic, $P2_1/c$	Monoclinic, $P2_1/c$
Temperature (K)	293	293	293	293
a, b, c (Å)	8.0841 (5), 8.5351 (4), 17.4924 (11)	7.816 (5), 8.605 (5), 11.558 (5)	8.058 (6), 16.703 (2), 9.025 (5)	13.139 (4), 7.796 (6), 13.139 (3)
α, β, γ (°)	90, 91.388 (6), 90	85.425 (5), 72.501 (5), 71.714 (5)	90, 106.149 (3), 90	90, 100.440 (11), 90
V ($Å^3$)	1206.60 (12)	703.8 (7)	1166.8 (11)	1323.6 (11)
Z	4	2	4	4
Radiation type	Mo Kα	Mo Kα	Mo Kα	Mo Kα
μ (mm^{-1})	12.6	11	13.07	11.72
Crystal size (mm)	0.14 x 0.14 x 0.12	0.23 x 0.18 x 0.13	0.18 x 0.17 x 0.12	0.33 x 0.28 x 0.19
Data collection				
Absorption correction	Multi-scan	Multi-scan	Multi-scan	Multi-scan
T_{min}, T_{max}	0.271, 0.313	0.187, 0.329	0.202, 0.303	0.113, 0.214
No. of measured, independent and observed [$I > 2\sigma(I)$] reflections	23878, 2610, 2179	5281, 2969, 2722	8421, 2540, 1870	26607, 2863, 2514
R_{int}	0.126	0.014	0.069	0.101
Refinement				
$R[F^2 > 2\sigma(F^2)]$, $wR(F^2)$, S	0.078, 0.194, 1.15	0.017, 0.042, 1.02	0.053, 0.128, 1.02	0.032, 0.079, 1.02
No. of reflections	2610	2969	2540	2863
No. of parameters	145	154	154	163
No. of restraints	0	0	0	0
$\Delta\rho_{max}$, $\Delta\rho_{min}$ (e $Å^{-3}$)	4.42, -1.92	1.03, -0.62	3.83, -1.21	1.59, -2.31
CCDC	1022615	1022616	1022617	1022618

Catalytic performance of various cyclometallated Au complexes and their pre-catalysts in oxazole synthesis. We recently reported that a cationic Au(III)–salen complex catalyzes the addition of terminal alkynes to *in situ* generated acyl iminium ions in an event that triggers a cycloisomerization domino reaction that ultimately results in oxazoles as products.[19] The merger of the otherwise incompatible A^3 coupling and cycloisomerization manifolds into a

single domino process is enabled by the loss of a sacrificial benzyl group on the imine nitrogen.[20] Synthetically, the method is attractive, as it generates building blocks for ligands and bioactive structures in a single step from simple, often commercially available, components. [21] The cyclometallated Au-complexes **3**, **6a/b** as well as their non-cyclometallated homologs **2**, **5a/b** were investigated as catalysts for this transformation (Table 3). The latter class of pre-catalysts are particularly interesting in this context as *in situ* cyclometallation under the reaction conditions would release a small amount of HCl, which should facilitate oxazole formation by promoting both the debenzylation and cycloisomerization steps in the reaction mechanism. The catalytic performance was benchmarked using the reaction between *N*-Bn imine **8a**, benzoyl chloride (**9a**), and phenyl acetylene (**10a**) to form oxazole **11a**. For comparative purposes, commercially available pyridine (py)$AuCl_3$ **7**[22] was also included as catalyst in the study.

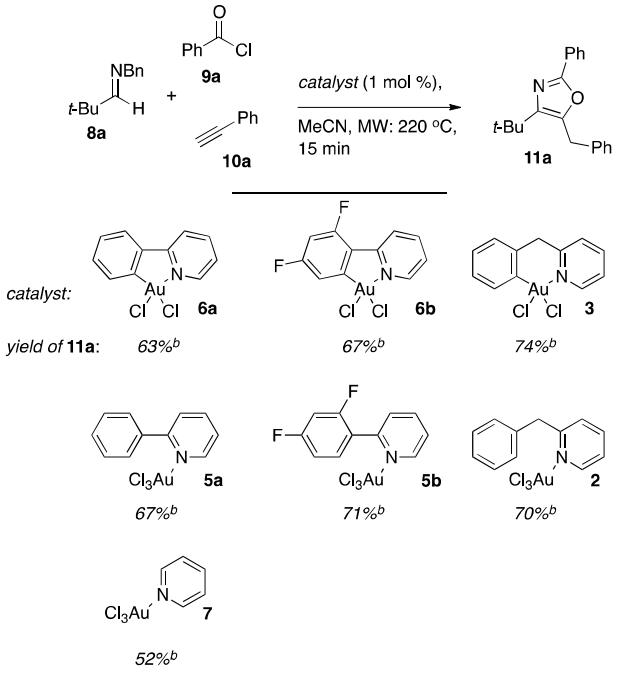
The cyclometallated aryl-pyridine complexes **3** and **6a/b** gave comparable yields although a slight advantage was found for the (bnpy)$AuCl_2$ **3**. This is in line with the earlier observation, that six-membered Au-metallacycles are more efficient than five-membered in the A^3-coupling.[10d] It is noteworthy that each of the non-cyclometallated catalysts **2** and **5a/b** gave similar results to that of the corresponding cyclometallated structures, which suggested that the active species in catalysis were the same in each pair of catalysts.

When employing (bnpyH)$AuCl_3$ **2** as a pre-catalyst, we were not able to detect the corresponding cyclometallated structure (bnpy)$AuCl_2$ **3** in the crude reaction mixture by ESI-MS or ^{1}H NMR. However, this is not surprising, as (bnpy)$AuCl_2$ **3** could be shown to decompose during the course of the reaction (15 min, 240 ^{o}C) (*vide infra*). We also observed that although we were unable to detect **3** in the reaction mixture, addition of additional starting material after a complete catalysis reaction, followed by re-heating of the resulting mixture to 240 ^{o}C for 15 minutes gave an additional 65% yield of oxazole **11a** (based on the second addition), demonstrating that the mixture was still catalytically active. An interpretation of this result is that either small amounts of highly active **3** remains in the mixture and/or that decomposition occurs at high temperatures to produce new active species such as gold nanoparticles that can contribute to catalysis. The latter notion is supported by the observed deposition of metallic gold in catalysis experiments using high catalyst loadings of **3** (>10 mol %).

In catalysis experiments using the non-cyclometalated complex **2** in acetonitrile-d_3, the ^{1}H NMR spectra indicated ligand exchange upon addition of the acyl chloride/imine components.

To investigate whether cyclometallation is possible under the reaction conditions, (bnpyH)$AuCl_3$ **2** was heated to 240 °C in acetonitrile-d_3. After 1 minute of heating, formation of ~10 mol % of the cyclometallated complex **3** was indeed observed in the ^{1}H NMR spectrum of the mixture, along with uncyclized precursor **2**. After an additional three minutes of heating however, only trace amounts of **3** remained, and after 15 minutes, no signals attributed to complex **3** could be detected.

Table 3. Comparison of gold complexes as catalysts for oxazole formation[a]



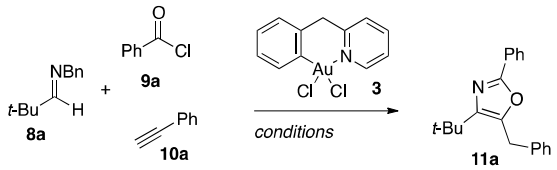
[a] *General conditions:* Reactions run on a 1.0 mmol scale (imine **8a**) with 2.0 equiv. phenyl acetylene (**10a**), 1.0 equiv. benzoyl chloride (**9a**), and 1 mol % of catalyst using microwave heating (220 °C, 15 min). [b] Yield measured by ^{1}H NMR spectroscopy using mesitylene as an internal standard.

We note however that a marked difference in efficiency remains between the pre-catalysts that can cyclometallate ((ppy)$AuCl_3$ **5a**, (dfppy)$AuCl_3$ **5b**, and (bnppy)$AuCl_3$ **2**) and (py)$AuCl_3$ **7**, which gives oxazole **11a** in 52% yield in the benchmark reaction. Cyclometallation under the reaction conditions thus appears viable, but the precise nature of the actual active catalytic species under the reaction conditions used remains ambiguous.

As the (bnpy)$AuCl_2$ **3** gave the best results in catalysis, oxazole formation was optimized for this complex (Table 4). An increase in the temperature to 240 °C was found to be beneficial giving a yield of 78% of oxazole **11a**. It is noteworthy that at this temperature, as little as 0.25 mol % catalyst could be used and still allow for formation of **11a** in 72% yield. The reaction

also proceeded neat and in process-friendly 2-Me-THF with this catalyst, but with a lower yield as a result.

Table 4. Optimization of oxazole formation catalyzed by (bnpy)$AuCl_2$ **3**[a]



Entry	T /°C	Catalyst-loading /mol %	t /min	Solvent	Yield /%[b]
1.	240	1	15	MeCN	78
2.	250	1	15	MeCN	78
3.	240	0.5	15	MeCN	77
4.	240	0.25	15	MeCN	70
5.	240	0.25	30	MeCN	72
6.	240	0.5	20	MeCN	77
7.	240	0.5	15	neat	54
8.	225	0.5	15	2-Me-THF	53

[a] *General conditions:* Reactions run on a 1.0 mmol scale (imine **8a**) with 1.0 equiv. benzoyl chloride (**9a**), 2.0 equiv. phenyl acetylene (**10a**), and 0.5 mol % of (bnpy)$AuCl_2$ **3** using microwave heating (240 °C, 15 min). [b] Measured by ^{1}H NMR spectroscopy using mesitylene as an internal standard.

Catalytic performance of (dfppy)$AuCl_2$ 6b and (dfppyH)$AuCl_3$ 5b in the A^3 coupling. Since the new fluorinated catalysts (dfppy)$AuCl_2$ **6b** and (dfppyH)$AuCl_3$ **5b** gave oxazole product in the three-component reaction, these complexes were also evaluated in the parent A^3 coupling under solvent-free conditions (Table 5). Both the cyclometallated complex and its non-cyclometallated counterpart gave clean formation of propargyl amine **14** using 1 mol % catalyst at 40 °C. The yield using the non-cyclometallated catalyst **5b** was essentially quantitative which is in line with what is found for (py)$AuCl_3$ or $AuCl_3$ under the same conditions. An immediate color change was seen upon addition of the amine component in these experiments suggesting a ligand exchange, and that (dfppyH)$AuCl_3$ **5b** acts primarily as a pre-catalyst. The (dfppy)$AuCl_2$ **6b** was also active in catalysis, however the isolated yield was lower than that reported for (bnpy)$AuCl_2$ **3** (83%)[10d] in the same transformation.

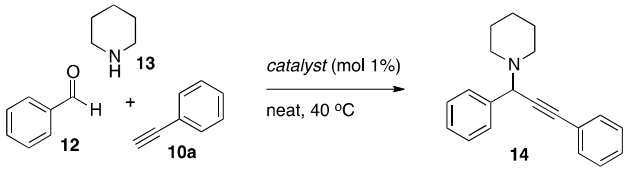


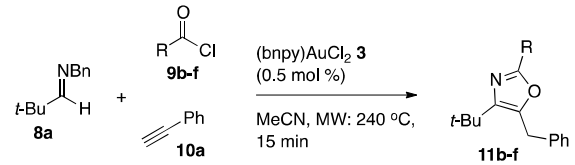
Table 5. Performance of (dfppyH)$AuCl_3$ **5b** and (dfppy)$AuCl_2$ **6b** in a benchmark A^3 coupling[a]

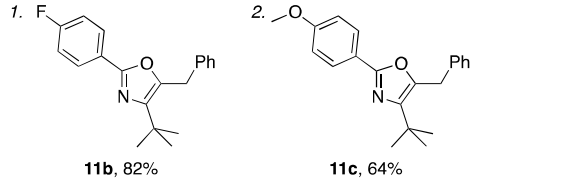
Entry	Catalyst	Solvent	Yield /%[b]
1.	(dfppyH)$AuCl_3$ **5b**	-	100
2.	(dfppy)$AuCl_2$ **6b**	-	71

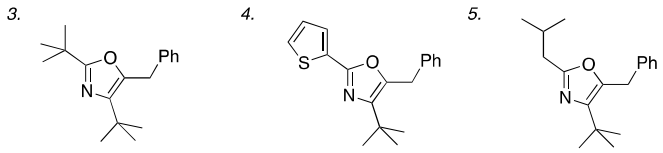
[a] *General conditions:* a) Reactions run at 40 °C using 1.0 mol % of the catalyst indicated on a 1.0 mmol scale (aldehyde), with 1.5 equiv. alkyne and 1.1 equiv. amine. The reactions were run for up to 24 hours or to full consumption of aldehyde (^{1}H NMR control); [b] Measured by ^{1}H NMR spectroscopy of the reaction crude using mesitylene as an internal standard.

Substrate scope for oxazole formation catalyzed by (bnpy)$AuCl_2$ 3. Outgoing from the optimized conditions for oxazole formation with (bnpy)$AuCl_2$ **3**, the substrate scope was investigated by varying the imine, alkyne and acyl chloride components.

Table 6. Substrate scope for oxazole formation varying the acyl chloride component[a]





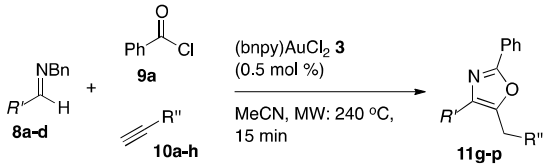


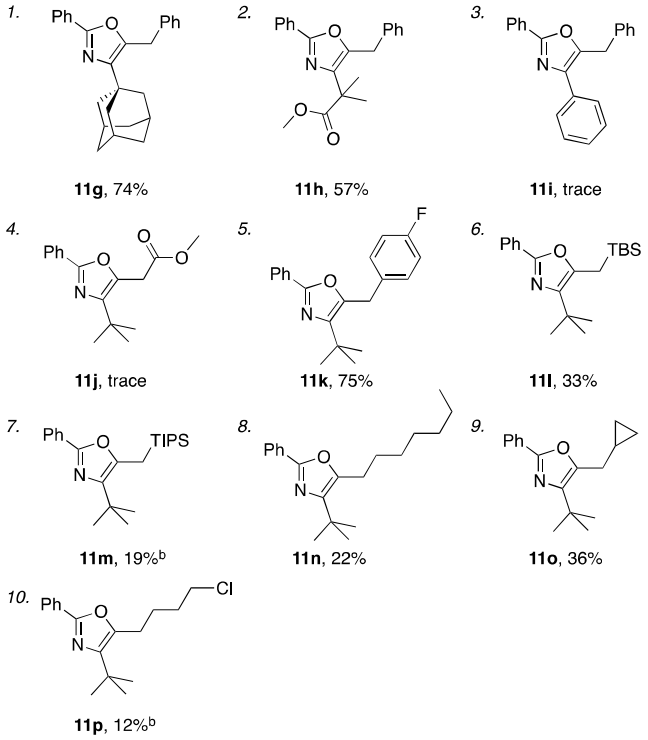
[a] *General conditions:* Reactions run on a 1.0 mmol scale (imine **8a**) with 1.0 equiv. acyl chlorides **9b-f**, 2.0 equiv. phenyl acetylene (**10a**), and 0.5 mol % of (bnpy)$AuCl_2$ **3** using microwave heating (240 °C, 15 min).

Under these conditions, a series of acyl chlorides including heterocyclic-, aliphatic- and aryl substituted examples all competently participated in oxazole formation with moderate to good yields as a result (Table 6). A catalyst loading of 0.5 mol % was sufficient to attain full

conversion of the starting materials in each case as evident by ^{1}H NMR spectroscopy of the crude reaction mixtures. The good turn over numbers with (bnpy)$AuCl_2$ **3** as the catalyst extended also to reactions with varying alkyne and imine components (Table 7). Similarly to what was previously seen with the Au-salen system, quaternary substitution at the α-position of the imine was however necessary for efficient reactions. Aromatic imines give at most traces of isolatable oxazole products with the majority of the mass after the reaction comprising unspecific decomposition. A difference compared to the Au-salen system is that lower yields are consistently obtained with linear aliphatic alkynes (Table 2, entry 8 and 10). The reason for this difference remains unclear.

Table 7. Substrate scope for oxazole formation varying the imine and alkyne components[a]





[a] *General conditions:* Reactions run on a 1.0 mmol scale (imines **8a**-**d**) with 1.0 equiv. benzyl chloride **9a**, 2.0 equiv. alkynes **10a**-**h**, and 0.5 mol % of catalyst (bnpy)$AuCl_2$ **3** using microwave heating (240 °C, 15 min). [b] The yields of oxazole **11m** and **11p** was measured by ^{1}H NMR spectroscopy using mesitylene as an internal standard.

CONCLUSIONS

In conclusion, a series of cyclometallated aryl-pyridine Au(III) complexes have been shown to efficiently catalyze oxazole formation in the three-component reaction between *N*-Bn imines, alkynes, and acyl chlorides. In particular, (bnpy)$AuCl_2$ **3** enables the use of down to 0.25 mol % of catalyst with good yields of the oxazole products in 15 minutes. The conditions are amenable to the synthesis of oxazoles varying in substitution at all positions (15 examples demonstrated) using down to one-tenth of the catalyst loading needed for the previously employed Au-salen complex. Importantly, as the reaction occurs under elevated temperatures, readily available non-cyclometallated pre-catalysts can also be exploited in this reaction without a significant loss of efficiency. Further studies on applications of this methodology are under way and will be reported in due course.

METHODS

General Experimental Methods. All reactions were carried out in oven-dried glassware under an atmosphere of nitrogen gas unless otherwise stated. Microwave reactions were performed using a Biotage Initiator. Imines **8a-d** were synthesized according to literature procedures.[3a] Catalysts (bnpy)$AuCl_2$ **3** and (ppy)$AuCl_2$ **6a** were synthesized following literature procedures. [14] Acetonitrile was distilled from CaH_2. All other solvents and reagents were bought from commercial suppliers and used as received. Yields are reported for isolated products after chromatographic purification unless otherwise stated. Spectroscopic data for known compounds ((bnpyH)$AuCl_3$ **2**,[23] (ppyH)$AuCl_3$ **5a**,[13] (dfppy)$AuCl_2$ **6b**,[15] oxazoles **11b-h**, **11k-l** and **11n-o**[3a], and propargyl amine **8a**[24]) were in agreement with literature data. ^{1}H, ^{19}F, and ^{13}C NMR spectra were recorded on a Bruker Avance 400 NMR spectrometer, with the residual solvent peak used as an internal reference. IR spectra were recorded on a Bruker Alpha spectrometer. Elemental analyses were performed by H. Kolbe Microanalytisches Laboratorium, Mülheim an der Ruhr, Germany.

General procedure for synthesis of $LAuCl_3$ complexes: The respective pyridine ligand (1.1 equiv.), dissolved in MeCN (10 mL), was added in one portion to $KAuCl_4$ in H_2O (10 mL). The reaction mixture was then stirred at room temperature for 2 h after which the formed yellow precipitate was collected by filtration. The precipitate was washed with water and MeCN and dried under reduced pressure.

(bnpyH)AuCl$_3$ 2: Prepared following the general procedure using 430 mg (1.14 mmol) $KAuCl_4$ and 212 mg (1.25 mmol) 2-benzylpyridine. Isolated as a yellow, amorphous powder (0.486 g, 90% yield). Pure by ^{1}H NMR spectroscopy. Dec. pt. 112.3-119.0 ^{o}C (melting, sample turns black).

(ppyH)AuCl$_3$ 5a: Prepared following the general procedure using 300 mg (0.79 mmol) $KAuCl_4$ and 135 mg (0.87 mmol) of 2-phenylpyridine. Isolated as a yellow amorphous powder (0.326 g, 90 % yield). Pure by ^{1}H NMR spectroscopy. Dec. pt. 198 ^{o}C (no melting, sample turns brown).

(dfppyH)AuCl$_3$ 5b: Prepared following the general procedure using 300 mg $KAuCl_4$ (0.79 mmol) and 167 mg (0.87 mmol) of 2-(2,4-difluorophenyl)pyridine. Isolated as a yellow amorphous powder (0.328 g, 84 % yield). ^{1}H NMR (500 MHz, acetone-d_6) δ 9.39 (ddd, J = 6.1, 1.5, 0.5 Hz, 1H), 8.54 (td, J = 7.8, 1.5 Hz, 1H), 8.17 (dtd, J = 7.8, 1.6, 0.5 Hz, 1H), 8.11 (ddd, J = 7.8, 6.1, 1.6 Hz, 1H), 7.99 (td, J = 8.5, 6.2 Hz, 1H), 7.44 – 7.32 (m, 2H). ^{13}C NMR (126 MHz, acetone-d_6) δ 165.6 (dd, J = 252.7, 12.0 Hz), 161.1 (dd, J = 253.1, 12.8 Hz), 153.8 (s), 152.2 (s), 143.9 (s), 133.6 (dd, J = 10.5, 2.7 Hz), 132.2 (d, J = 1.8 Hz), 128.9 (s), 123.1 (dd, J = 14.8, 4.0 Hz), 113.1 (dd, J = 22.2, 3.8 Hz), 106.1 (t, J = 25.9 Hz). ^{19}F NMR (376 MHz, acetone-d_6) δ 71.8 (d, J = 10.0 Hz), 68.2 (d, J = 10.0 Hz). FTIR (ATR, neat): 3105 (w), 3079 (w). 1614 (m), 1603 (m), 1591 (m), 1566 (m), 1514 (s), 1479 (m) cm^{-1}. Anal. Calc. for $C_{11}H_7AuCl_3F_2N$: C, 26.72; H, 1.43; N, 2.83. Found C, 26.93, H, 1.41; N, 2.85. Mp. 210.2–211.0 ^{o}C.

(dfppy)AuCl$_2$ 6b: A suspension of (dfppyH)$AuCl_3$ **5b** (0.076 g, 0.166 mmol) in water (5 mL) was heated using microwave radiation with the ceiling temperature set to 180 ºC and the sample absorption set to "high" for 7 hours. After cooling, the mother liquor was decanted and the remaining solid residue was washed with water (3 x 1.5 mL) and dried under a stream of air to give (dfppy)$AuCl_2$ **6b** as a white powder (0.042 g, 59%) pure by ^{1}H NMR spectroscopy. Dec. pt. 279.1–282.0 ^{o}C (melting, sample turns orange).

General procedure for A^3 coupling reactions. The respective gold complex (0.01 mmol) was charged in a vial under an air atmosphere and phenylacetylene (165 µl, 1.5 mmol) was added. Piperidine (109 µl, 1.1 mmol) and benzaldehyde (101 µl, 1.0 mmol) was then added sequentially and the resulting homogenous mixture was heated to 40 ^{o}C for 24 h. The reaction mixture was then cooled to ambient temperature and mesitylene (70 µl, 0.5 mmol) was added. The product to mesitylene ratio was determined through integration of the propargyl (product) and aryl (mesitylene) signals in the ^{1}H NMR spectra.

General procedure for optimization of Au-catalyzed oxazole formation. To a microwave vial, charged with the respective gold catalyst and flushed with nitrogen, was added the solvent indicated (0.5 mL) followed by addition of *N*-Bn-imine **8a** (0.21 mL, 1.0 mmol), phenylacetylene (**10a**) (0.23 mL, 2.0 mmol), and benzoyl chloride (**9a**) (0.12 mL, 1.0 mmol) in short sequence. The resulting mixture was immediately heated by microwave irradiation to the temperature indicated (sample absorption set to "high"). After the time indicated, the reaction was cooled to room temperature and mesitylene (0.5 equiv.) was added as an internal standard. A sample of the reaction mixture was diluted with $CDCl_3$ and the ^{1}H NMR yield was quantified by measuring the product-to-mesitylene ratio through integration of the *tert*-butyl signal of the oxazole **11a** (^{1}H NMR δ = 1.37 ppm) and methyl signal in mesitylene (^{1}H NMR δ = 2.28 ppm) in the ^{1}H NMR spectra.

General procedure for (bnpy)$AuCl_2$ 3 catalyzed oxazole synthesis. To a microwave vial, charged with (bnpy)$AuCl_2$ **3** (2.2 mg, 0.005 mmol) and flushed with nitrogen gas, was added anhydrous MeCN (0.5 mL). Imine (1.0 mmol), alkyne (2.0 mmol) and acyl chloride (1.0 mmol) were then added in short sequence. The resulting mixture was immediately heated for 15 min by microwave irradiation using a ceiling temperature of 240 °C and a sample absorption set to "high". The reaction mixture was then cooled to room temperature. The mixture was diluted with CH_2Cl_2 and a small amount of silica gel was added. The resulting slurry was concentrated under reduced pressure to yield a dry powder. Purification by flash chromatography (elution with EtOAc/petroleum ether) gave the corresponding oxazole products.

Crystallography. Intensity data were collected with an Oxford Diffraction Excalibur 3 system, using ω-scans and Mo Kα (λ = 0.71073 Å) radiation.[25] The data were extracted and integrated using Crysalis RED.[26]. The structures were solved by direct methods and refined by full-matrix least-squares calculations on F^2 using SHELXTL.[27] Molecular graphics were generated using CrystalMaker 9.0.3. CCDC deposition numbers 1022615-1022618.

ACKNOWLEDGEMENTS

We thank the Swedish Research Council, the Carl Trygger Foundation, Knut and Alice Wallenberg foundation, The Royal Physiographical Society, and Lund University for generous support.

† *Electronic Supplementary Information (ESI) available*: Copies of ^{1}H NMR and ^{13}C NMR, ^{19}F NMR spectra for (dfppyH)$AuCl_3$ **5b**. SC-XRD data for compounds **2**, **3**, **5b**, and **6b** in .cif format. See DOI: 10.1039/b000000x/

REFERENCES

[1] For recent reviews see: (a) M. Rudolpha and A. S. K. Hashmi, *Chem. Soc. Rev.,* 2012, **41**, 2448; (b) D. J. Gorin and F. D. Toste, *Nature*, 2007, **446**, 395; (c) N. D. Shapiro and F. D. Toste, *Synlett*, 2010, **5**, 675; (d) S. Wang, G. Zhang and L. Zhang, *Synlett*, 2010, **5**, 692.

[2] (a) H. Schmidbaur and A. Schier, *Arab. J. Sci. Eng*., 2012, **37***,* 1187; A. S. K. Hashmi, *Chem. Rev*., 2007, **107**, 3180; (b) N. Krause and C. Winter, *Chem. Rev*., 2011, **111**, 1994.

[3] (a) H. v. Wachenfeldt, P. Röse, F. Paulsen, N. Loganathan and D. Strand, *Chem. Eur. J.*, 2013, **19**, 7982; See also: (b) H. v. Wachenfeldt, F. Paulsen, A. Sundin and D. Strand, *Eur. J. Org. Chem.,* 2013, 4578.

[4] M. Pažický, A. Loos, M. J. Ferreira, D. Serra, N. Vinokurov, F. Rominger, C. Jäkel, A. S. K. Hashmi and M. Limbach, *Organometallics* 2010, **29**, 4448.

[5] T. E. Müller, M. Grosche, E. Herdtweck, A.-K. Pleyer, E. Walter and Y.-K. Yan, *Organometallics* 2000, **19,** 170.

[6] (a) A.S.K. Hashmi, J. P. Weyrauch, M. Rudolph and E. Kurpejović, *Angew. Chem., Int. Ed*., 2004**, 43***,* 6545.

[7] (a) E. Langseth, C. H. Görbitz, R. H. Heyn and M. Tilset, *Organometallics*, 2012**, 31***,* 6567.

[8] For recent reviews see: (a) Z. Li, C. Brouwer and C. He, *Chem. Rev*., 2008, **108**, 3239; (b) A. Arcadi, *Chem. Rev.*, 2008, **108**, 3266.

[9] For recent review see: D. J. Gorin, B. D. Sherry and F. D. Toste, *Chem. Rev.*, 2008, **108**, 3351.

[10] For recent reviews see: (a) V. A. Peshkov, O. P. Pereshivkoa and E. V. Van der Eycken, *Chem. Soc. Rev.*, 2012, **41**, 3790; For lead examples, see: (b) C. Wei and C.-J. Li, *J. Am. Chem. Soc.*, 2003, **125**, 9584; (c) V. K.-Y. Lo, Y. Liu, M.-K. Wong and C.-M. Che, *Org. Lett*., 2006, **8**, 1529; (d) K. K.-Y. Kung, V. K.-Y. Lo, H.-M. Ko, G.-L. Li, P.-Y. Chan, K.-C. Leung, Z. Zhou, M.-Z. Wang, C.-M. Che and M.-K. Wong, *Adv. Synth. Catal*., 2013, **355**, 2055.

[11] For recent review, see: (a) S. Bresciani, and N. C. O. Tomkinson, *Heterocycles*, 2014, **89**, 2479; (b) G. Abbiati and E. Rossi, *Beilstein J. Org. Chem*., 2014, **10**, 481; (c) A. V. Gulevich, A. S. Dudnik, N. Chernyak and V. Gevorgyan, *Chem. Rev.* 2013, **113**, 3084; (d) M. Rudolph and A. S. K. Hashmi, *Chem. Commun*., 2011, **47**, 6536; (e) A. S. K. Hashmi, *Pure Appl. Chem*., 2010, **82**, 657.

[12] For lead examples of multicomponent oxazole synthesis see: (a) E. Merkul, O. Grotkopp and T. J. J. Müller, *Synthesis*, 2009, 502; (b) B. Wu, J. Wen, J. Zhang, J. Li, Y.-Z. Xiang and X.-Q. Yu, *Synlett*, 2009, 500; (c) D. A. Black and B. Arndtsen, *Tetrahedron*, 2005, **61**, 11317.

[13] C. Constable and T. A. Leese, *J. Organomet. Chem.,* 1989, **363**, 419.

[14] A. P. Shaw, M. Tilset, R. H. Heyn and S. Jakobsen, *J. Coord. Chem.,* 2011, **64**, 38.

[15] J. A. Garg, O. Blacque and K. Venkatesan, *Inorg. Chem.,* 2011, **50**, 5430.

[16] (a) M. Kondrashov, S. Raman and O. F. Wendt, *Chem. Commun.* 2015, **51**, 911; See also (b) Q. Wu, C. Du, Y. Huang, X. Liu, Z. Long, F. Song and J. You *Chem. Sci.* 2015, **6**, 288.

[17] D. Kalyani, A. R. Dick, W. Q. Anani and M. S. Sanford, Tetrahedron, 2006, 62, 11483

[18] For SC-XRD structure of **5a** see: (a) X.-P. Zhang, G. Yang, L. Wang, S. W. Ng *Acta Cryst.* 2007, **E63**, m1582; for SC XRD structure of **6a** see: (b) D. Fan, C.-T. Yang, J. D. Ranford, P. F. Lee and J. J. Vittal *Dalton. Trans.* 2003, 2680.

[19] A. D. Black and B. A. Arndtsen, *Org. Lett*., 2004, **6**, 1107.

[20] For a detailed mechanistic discussion on this process, see references 3a and 3b.

[21] X. Sun, P. Janvier, G. Zhao, H. Bienayme and J. Zhu, *Org. Lett*., 2001, **3**, 877.

[22] L. Cattalini and M. L. Tobe, *Inorg. Chem.* 1966, **5**, 1145.

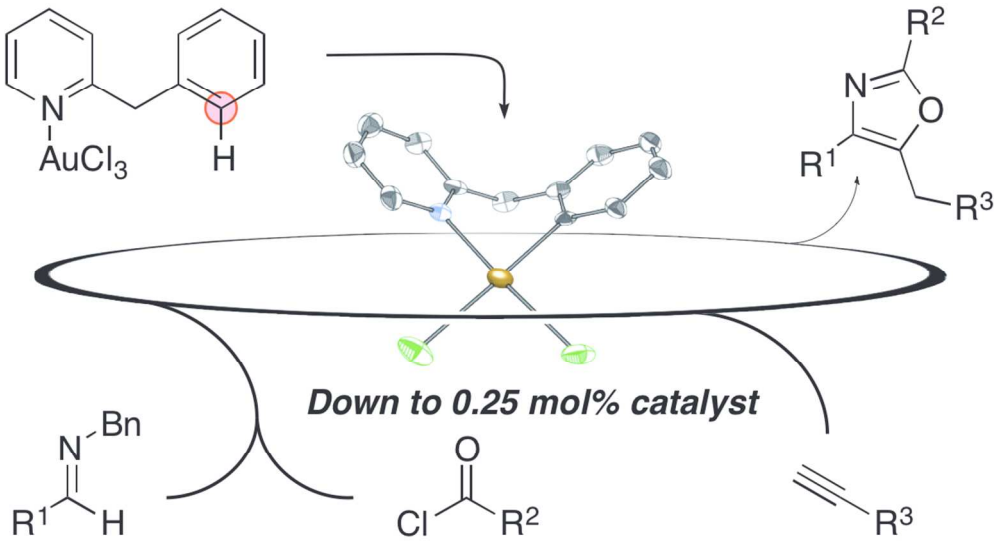
[23] M. A. Cinellu, A. Zucca, S. Stoccoro, G. Minghetti, M. Manassero and M. Sansoni, *J. Chem. Soc., Dalton Trans.,* 1995, 2865.

[24] P-H. Li and L. Wang, *Chin. J. Chem*., 2005, **23**, 1076.

[25] Crysalis CCD; Oxford Diffraction Ltd.: Abingdon, Oxfordshire, UK (2005)

[26] Crysalis RED; Oxford Diffraction Ltd.: Abingdon, Oxfordshire, UK (2005)

[27] G. M. Sheldrick, *Acta Cryst*., 2008, A64, 112–122.



102x55mm (300 x 300 DPI)