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Gold-catalysed cycloisomerisation reactions of 2-(2-propynyl)pyridine *N*-oxides leading to indolizinones†

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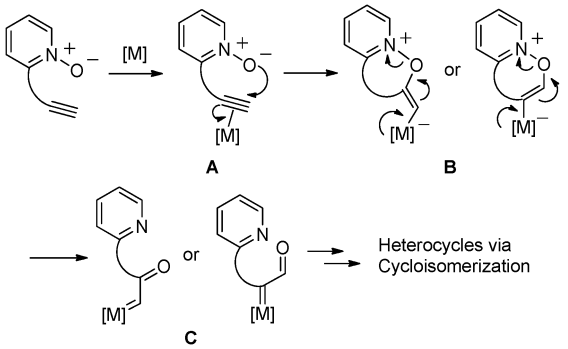
Gold(I)-catalysed tandem oxygen-transfer/cycloisomerisation reaction of 2-(2-propynyl)pyridine *N*-oxides provides an atom-economical route to indolizinone frameworks.

Indolizinones, the structure of which is closely related to that of indolizines which exhibit strong anti-inflammatory, anti-HIV, and anti-leukemia activity, have been exploited as privileged structural motifs in the development of biologically active molecules.[1] Development of efficient and selective constructions of these heterocycles with different substitution patterns from readily available starting materials under mild conditions remains an important task in synthetic chemistry. In this regard, transition metal-catalysed cycloisomerisation reaction of heteroatom-functionalized alkynes has received considerable attention, since they provide a wide variety of complexed heterocycles with high atom-efficiency.[2] π-Alkyne metal complexes are key intermediates capable of undergoing a wide range of reactions. Perhaps most commonly, they induce the addition of internal nucleophiles with a suitable length of tethers leading to zwitterion (or metallocarbenoid) intermediates. A variety of oxygen species may serve as the nucleophiles: carbonyl (C=O),[2,3] epoxides,[2,4] amine *N*-oxides (R_3N^+–O^-),[5] nitrones,[6] nitro,[7] and sulfoxides (R_2S=O)[8] have been employed with various transition-metal catalysts. In line with our recent interest in the development of facile and efficient cycloisomerisation reactions leading to heterocycles,[9] we applied oxygen transfer from pyridine *N*-oxides[10] to alkynes activated with transition metals **A** to the generation of zwitterions **B** or metallocarbenoids **C** (Scheme 1).[11] Since the resulting metallocarbenoids **C** possess reactive pyridyl groups, they might be further converted into nitrogen-containing heterocycles. Herein, we wish to report gold-catalysed cycloisomerisation of 2-(2-propynyl)pyridine *N*-oxides leading to indolizinones *via* acyl[(2-pyridyl)methyl]carbenoid complexes.[12]

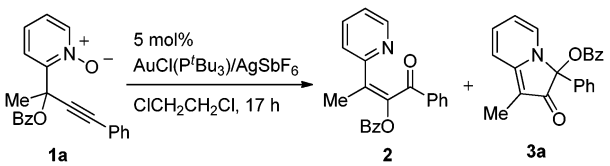
We reported the atom-economical generation of (2-furyl)-carbene complexes using carbonyl–ene–yne compounds as



Scheme 1 Transition metal-induced oxygen-transfer in pyridine *N*-oxides involving an alkyne moiety.

their precursors.[13] In the course of our continuing studies on such reactive intermediates, we have found a novel method for the generation of carbene complexes bearing a pyridyl group from pyridine *N*-oxides having alkyne moieties. When pyridine *N*-oxide **1a** was treated with 5 mol% of $AuCl(P^tBu_3)$/$AgSbF_6$ in $ClCH_2CH_2Cl$ at rt (Scheme 2), β-pyridylenone **2** ($E : Z$ = 92 : 8) and indolizinone **3a** were obtained in 59% and 41% yields, respectively. The relative stereochemistry of **3a** was established by X-ray crystallography.[14] When the reaction was carried out at 50 °C, the total yield of **2** decreased to 25%, whereas the yield of **3a** raised up to 75%. These results indicate that **3a** might be formed by the cycloisomerisation of **2** under the reaction conditions.

This interesting result stimulated us to optimize conditions for the cycloisomerisation of **1a** leading to indolizinone **3a**. The results are summarized in Table 1. First, reactions of **1a** in the presence of other gold catalysts were examined. While reactions were generally sluggish in the presence of neutral gold catalysts, such as AuCl, $AuCl_3$, and $AuCl(P^tBu_3)$ (entries 1–3), cationic gold species prepared *in situ* from the reaction of



Scheme 2 Gold(I)-catalysed cycloisomerisation of **1a**.

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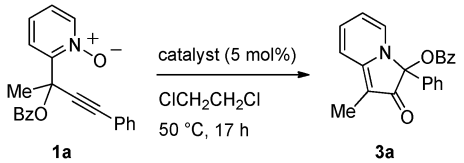
Table 1 Transition metal-catalysed cycloisomerisation of **1a**[a]



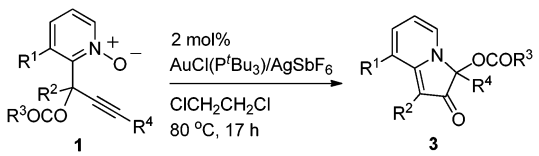
Entry	Catalyst	Yield of **3a**[b] (%)
1	AuCl	6
2	$AuCl_3$	11
3	$AuCl(P^tBu)_3$	29
4	$AuCl(PPh)_3/AgSbF_6$	50
5	$(IPr)AuCl/AgSbF_6$	24
6[c]	$AuCl(P^tBu)_3/AgSbF_6$	86
7[c,d]	$AuCl(P^tBu)_3/AgSbF_6$[e]	86

[a] Reaction conditions: **1a** (0.20 mmol) in $ClCH_2CH_2Cl$ (2.5 mL) was heated at 50 °C in the presence of catalyst (5 mol%) for 17 h. [b] Isolated yields. [c] At 80 °C. [d] (*Z*)-**2** was obtained in 14% yield. [e] 2 mol%. IPr = 1,3-bis(2,6-diisopropylphenyl)imidazol-2-ylidene.

equimolar amounts of gold and silver salts exhibited much higher catalytic activity (entries 4 and 5). The combination of $AuCl(P^tBu_3)/AgSbF_6$ was the catalyst of choice for this cycloisomerisation and the yield of **3a** improved to 86% when the reaction temperature was increased to 80 °C (entry 6). Furthermore, we found that reducing the catalyst loading to 2 mol% did not influence the selectivity and efficiency of the reaction (entry 7).[15] The use of other metal catalysts decreased the reaction efficiency.[16] Screening of solvents also identified $ClCH_2CH_2Cl$ to be optimal.[17] It is noteworthy that the (*Z*)-isomer of β-pyridylenone **2** was obtained in 14% yield as a by-product under the optimized reaction conditions (entry 7).

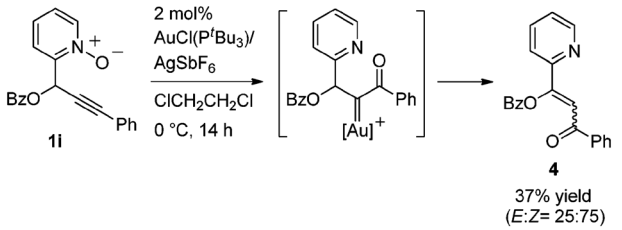
With the optimized reaction conditions in hand, we next examined the substrate scope of the present cycloisomerisation reaction. The results are summarized in Table 2. Both pivalate **1b** and acetate **1c** can serve as substrates for this reaction, affording the corresponding indolizinones **3b** and **3c** in 82% and 71% yields, respectively (entries 1 and 2). An excellent yield of the product was obtained in the reaction of ethyl group substituted pyridine *N*-oxide **1d** (entry 3). The reaction of **1e** and **1f** having 2-naphthyl and butyl groups at the alkyne

Table 2 Gold(I)-catalysed cycloisomerisation of **1**[a]



Entry	R^1	R^2	R^3	R^4		Product	Yield[b] (%)
1[c]	H	Me	^{t}Bu	Ph	**1b**	**3b**	82
2	H	Me	Me	Ph	**1c**	**3c**	71
3	H	Et	Ph	Ph	**1d**	**3d**	96
4	H	Me	Ph	2-Naph	**1e**	**3e**	66
5	H	Me	Ph	^{n}Bu	**1f**	**3f**	64
6	H	Me	Ph	H	**1g**	**3g**	0
7	$-(CH_2)_3-$		Ph	Ph	**1h**	**3h**	78

[a] Reaction conditions: **1** (0.40 mmol) in $ClCH_2CH_2Cl$ (5.0 mL) was heated at 80 °C in the presence of $AuCl(P^tBu)_3/AgSbF_6$ (2 mol%). [b] Isolated yields. [c] For 5 h.



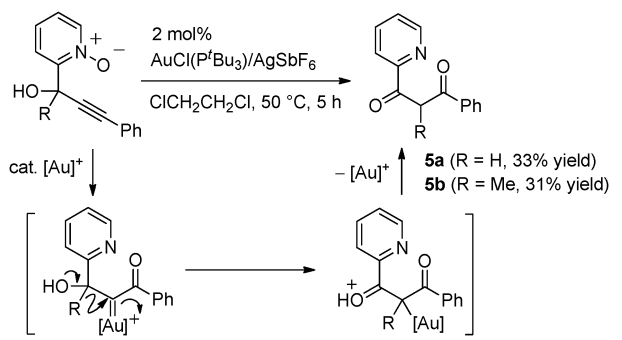
Scheme 3 Gold(I)-catalysed isomerisation of **1i**.

terminus produced the corresponding 9-benzyloxyindolizinones **3e** and **3f** in moderate yields, respectively (entries 4 and 5). In contrast, terminal alkyne **1g** decomposed under the reaction conditions and no products being able to characterize were observed (entry 6). The reaction of alkyne-substituted 5,6,7,8-tetrahydroquinoline *N*-oxide **1h** proceeded to give nitrogen-containing tricycle **3h** in good yield (entry 7).

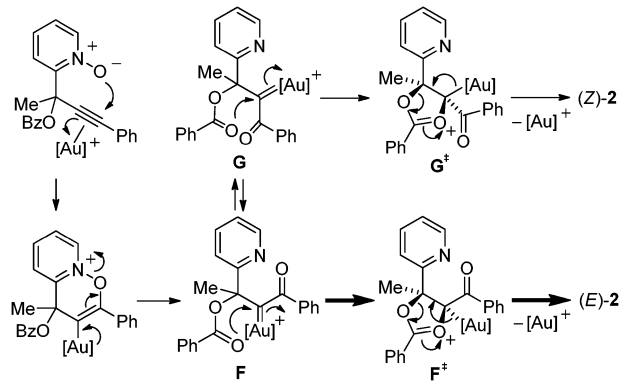
Interestingly, **1i** which has a hydrogen atom at the propargyl position afforded β-pyridylenone **4** in 37% yield as a mixture of stereoisomers without the formation of indolizinone (Scheme 3). The formation of **4** can be rationalized by invoking 1,2-hydride shift of the acyl[(2-pyridyl)methyl]-carbene complex generated from **1i**. This observation indicates that the migration of a benzoyloxy group to the carbene carbon is essential in the cycloisomerisation of **1** leading to the indolizinone.

When the reaction of alcohols without a benzoyl moiety was carried out, diketones **5a** and **5b** were obtained in 33% and 31% yields, respectively (Scheme 4). Diketones were formed *via* the domino process that includes the generation of carbene species and 1,2-rearrangement of H or Me followed by protodemetalation. This result supports that the present reaction proceeds through 6-*endo*-*dig* cyclization *via* the nucleophilic attack of the oxygen atom of pyridine *N*-oxides to alkyne moieties.

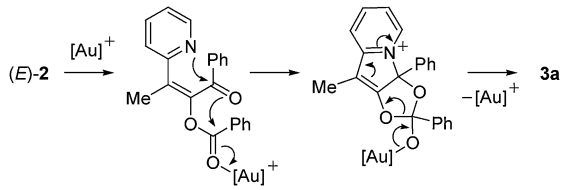
On the basis of the aforementioned observations,[18] the most plausible mechanism for the cycloisomerisation of **1a** is proposed in Schemes 5 and 6. First, acyl[(2-pyridyl)methyl]-carbene complex **F** is formed through 6-*endo*-*dig* cyclization *via* the nucleophilic attack of the oxygen atom of pyridine *N*-oxides to alkyne moieties activated by the cationic gold catalyst followed by N–O bond cleavage (oxygen-transfer).[10] Carbene complex **F** is then converted to (*E*)-**2** through the migration of a benzoyloxy group to the carbene center *via* the transient **F**‡.[19] The fact that (*E*)-**2** was obtained as a major isomer at room temperature can be explained by assuming the



Scheme 4 Gold(I)-catalysed isomerisation of alcohols.



Scheme 5 Regioselective formation of β-pyridylenone **2**.



Scheme 6 Cycloisomerisation of (*E*)-**2** leading to **3a**.

facile attack of a carbonyl moiety to a carbenoid center in rotamer **F** (*via* transition state $\mathbf{F}^{\ddagger}$), which is kinetically favoured (see also Scheme 2).[20] On the other hand, the amount of (*Z*)-**2** formed was slightly affected by the reaction temperature (5–8%), at which migration of a benzoyloxy group takes place *via* rotamer **G** and transient $\mathbf{G}^{\ddagger}$. At further elevated temperature, (*E*)-**2** only undergoes cycloisomerisation *via* the intramolecular attack of pyridyl nitrogen to the gold catalyst-activated carbonyl group to furnish indolizinone **3a** along with regeneration of the catalyst (Scheme 6).[21]

In conclusion, we have demonstrated gold-catalysed oxygen-transfer and cycloisomerisation cascade of 2-(2-propynyl)-pyridine *N*-oxides leading to 9-acyloxyindolizinones. It is noted that the gold catalyst serves as a π- and a σ-acid catalyst.

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14 For X-ray crystal analysis data of **3a**, see ESI† (CCDC 869886).

15 When isolated $^{t}Bu_3PAuSbF_6$ was used as a catalyst, **3a** was obtained in 86% yield.

16 Other transition metal catalysts produced **3a** in the following yields. $AgSbF_6$: 15%, $PtCl_2$: 17%, $[RuCl_2(CO)_3]_2$: 8%, $[Rh(OAc)_2]_2$: 0%.

17 **3a** was obtained in 31% yield in MeCN and 50% yield in $MeNO_2$, respectively, at 50 °C in the presence of 5 mol% of $AuCl(PPh_3)$/$AgSbF_6$.

18 See ESI† for the further discussion into the reaction mechanism.

19 The possibility that pyridylenones **2** are formed through 1,2-rearrangement of a benzoyloxy group followed by oxygen-transfer from pyridine *N*-oxide to the generated carbene complexes, or 1,3-rearrangement of a benzoyloxy group followed by oxygen-transfer from pyridine *N*-oxide to the terminal position of the resulting allene cannot be ruled out completely. For the gold-catalysed allene formation and oxygen-transfer from sulfoxides to carbenes, see: (*a*) P. Mauleón, J. L. Krinsky and F. D. Toste, *J. Am. Chem. Soc.*, 2009, **131**, 4513; (*b*) C. A. Witham, P. Mauleón, N. D. Shapiro, B. D. Sherry and F. D. Toste, *J. Am. Chem. Soc.*, 2007, **129**, 5838.

20 Gold-catalysed isomerization of **1a** at 0 °C selectively afforded (*E*)-**2** in 12% yield without forming (*Z*)-**2**. For X-ray crystal analysis data of (*E*)-**2**, see ESI† (CCDC 869885).

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