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# Gold-catalyzed (4+3)-annulations of 2-alkenyl-1-alkynylbenzenes with anthranils with alkyne-dependent chemoselectivity: skeletal rearrangement *versus* non-rearrangement†

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Two distinct (4+3)-nitroso annulations between 1,5-enynes and anthranils have been developed to access tetrahydro-1*H*-benzo[*b*]azepine derivatives; the chemoselectivity varies with the types of alkynes. Terminal alkyne substrates deliver benzo[*b*]azepine derivatives *via* a novel skeletal rearrangement while internal 1,5-enynes afford products without a rearrangement process. To elucidate the mechanism of rearrangement, we performed <sup>13</sup>C- and <sup>2</sup>H-labeling experiments to identify the gold-containing isobenzofulvene intermediates, but their formation relies on the presence of anthranils.

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## Introduction

Cyclic nitroso species (N–O) are widespread functionalities in numerous bioactive molecules and natural products.<sup>1</sup> Tetrahydro-1*H*-benzo[*b*]azepines bearing a hydroxyl (I–IV) represent a family of privileged seven-membered azacycles,<sup>2</sup> possessing potent activities in antiparasitic disease, antidiuretic hormone receptors and β<sub>2</sub> adrenergic agonists.<sup>3</sup> Synthetic procedures for compounds I–IV are generally long and tedious.<sup>2</sup> A short route to construct tetrahydrobenzo[*b*]azepine cores involves the development of stereoselective (4+3)-annulations between anthranils and all-carbon 1,3-dipoles (eqn (1)), but only donor–acceptor cyclopropanes were shown to be applicable substrates.<sup>4</sup> We are aware of no π-bond motifs that can serve as effective 1,3-dipoles.<sup>5</sup>

Synthetic interest in isoxazoles and anthranils is rapidly growing in Au- and Pt-catalysis because of their various annulations with alkynes.<sup>6,7</sup> Nevertheless, these hetero-aromatics serve as nucleophiles that attack π-alkynes *via* a N- or O-attack route, inevitably cleaving the N–O bonds; selected examples are provided in eqn (2) and (3). We sought the first (4+3)-nitroso annulations using alkyne-based 1,3-dipoles and anthranils. This work reports two distinct (4+3)-annulations of 1,5-enynes with anthranils; interestingly, the chemoselectivity varies with the alkynes. Terminal 1,5-enynes **1** (R = H) afford seven-membered nitroso

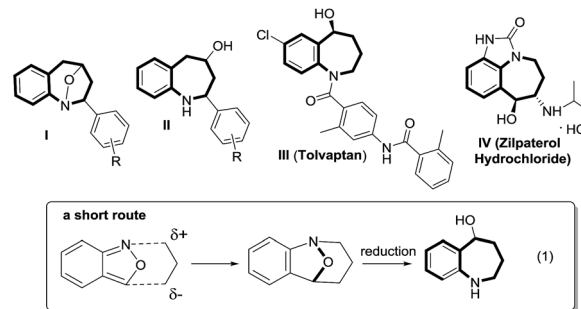
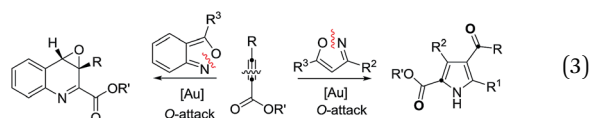
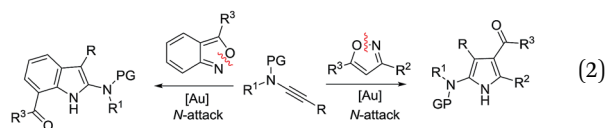


Fig. 1 Representative molecules and a postulated short route.

heterocycles **3** *via* an unprecedented rearrangement in gold catalysis;<sup>8</sup> the mechanism of this novel rearrangement has been elucidated. Annulation products **5** derived from internal alkynes **4** are not skeletally rearranged, but are elaborated into various benzo[*b*]azepine frameworks (Fig. 1).

Annulations with N–O cleavages

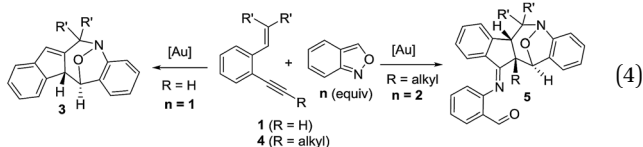


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This work: (4+3)-nitroso annulations



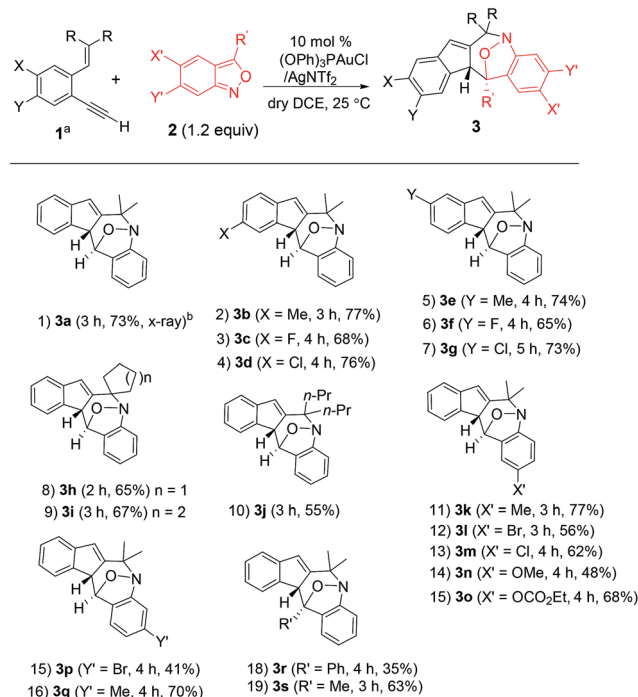
## Results and discussion

We optimized the reactions of terminal 1,5-enyne **1a** with anthranil **2a** (1.2 equiv.) using various gold catalysts; the results are shown in Table 1. Operations in dry dichloroethane (DCE, 25 °C) with L'AuCl/AgNTf<sub>2</sub> (L' = P(*t*-Bu)<sub>2</sub>(*o*-biphenyl), IPr, PPh<sub>3</sub>) afforded seven-membered nitroso product **3a** in 8–68% yield (entries 1–3), with P(*t*-Bu)<sub>2</sub>(*o*-biphenyl)AuCl/AgNTf<sub>2</sub> being the most effective. To our delight, (PhO)<sub>3</sub>PAuCl/AgNTf<sub>2</sub> increased the yield of the desired **3a** up to 73% (entry 4); different silver salts as those in (PhO)<sub>3</sub>PAuCl/AgX (X = SbF<sub>6</sub> and OTf) delivered compound **3a** in relatively low yields (35–42%, entries 5 and 6). With (PhO)<sub>3</sub>PAuCl/AgNTf<sub>2</sub>, the yields of compound **3a** in different solvents were as follows: DCM (62%), acetonitrile (30%) and MeNO<sub>2</sub> (0%, entries 7–9). AgNTf<sub>2</sub> alone was completely inactive (entry 10). The molecular structure of compound **3a** was characterized by X-ray diffraction<sup>9</sup> to reveal a (4+3)-annulation with an intact N–O bond. In the absence of anthranil **2a**, 1,5-enyne **1a** was isomerized by a gold catalyst to afford 1'-methylvinyl-1*H*-indene **1a'**, which was structurally unrelated to our target **3a**. Anthranil **2a** is obviously indispensable to enabling the (4+3)-annulations with structural rearrangement.

Under these optimized conditions, we assess the generality of these new annulations with various terminal 1,5-enynes and

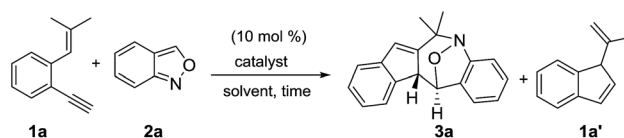
anthranils. The results are provided in Table 2; only a single diastereomeric product was obtained for all instances. In several instances, vinyl-1*H*-indene **1a'** was present as

Table 2 Reactions with terminal 1,5-enynes and anthranils



<sup>a</sup> [1] 0.20 M. <sup>b</sup> Yields of the products were reported after isolation on a silica gel column.

Table 1 Optimized conditions over various gold catalysts



Entry	Catalyst <sup>a</sup> (mol %)	2a <i>n</i> equiv.	Solvent	Time (h)	Temp ( <i>t</i> °C)	Yields <sup>b</sup> (%)		
						1a	3a	1a'
1	LAuCl/AgNTf <sub>2</sub>	1.2	DCE	5	25	—	68	—
2	IPrAuCl/AgNTf <sub>2</sub>	1.2	DCE	15	25	25	8	—
3	Ph <sub>3</sub> PAuCl/AgNTf <sub>2</sub>	1.2	DCE	12	25	—	35	—
4	(PhO) <sub>3</sub> PAuCl/AgNTf <sub>2</sub>	1.2	DCE	4	25	—	73	—
5	(PhO) <sub>3</sub> PAuCl/AgSbF <sub>6</sub>	1.2	DCE	10	25	10	35	—
6	(PhO) <sub>3</sub> PAuCl/AgOTf	1.2	DCE	2	60	—	42	—
7	(PhO) <sub>3</sub> PAuCl/AgNTf <sub>2</sub>	1.2	DCE	10	25	—	62	—
8	(PhO) <sub>3</sub> PAuCl/AgNTf <sub>2</sub>	1.2	MeCN	10	25	—	30	—
9	(PhO) <sub>3</sub> PAuCl/AgNTf <sub>2</sub>	1.2	MeNO <sub>2</sub>	20	25	80	—	—
10	AgNTf <sub>2</sub>	1.2	DCE	24	25	85	>5	—
11	(PhO) <sub>3</sub> PAuCl/AgNTf <sub>2</sub>	0	DCE	4	25	—	—	65

<sup>a</sup> **1a** (0.20 M), **2a** (1.2 equiv.). <sup>b</sup> Product yields are given after purification on a silica gel column, L = P(*t*-Bu)<sub>2</sub>(*o*-biphenyl), IPr = 1,3-bis(diisopropylphenyl)imidazol-2-ylidene.

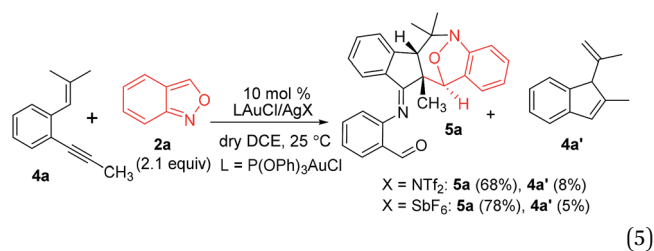


a byproduct in a minor proportion (5–15%). The annulations of anthranil **2a** (1.2 equiv.) with terminal 1,5-enynes **1b–1d** bearing various 4-phenyl substituents ( $X = \text{Me}$ ,  $\text{Cl}$ , and  $\text{F}$ ) proceeded smoothly to yield **3b–3d** in 68–77% yields (entries 2–4). For their 5-phenyl analogues **1e–1g**, the resulting annulation products **3e–3g** ( $Y = \text{Me}$ ,  $\text{Cl}$  and  $\text{F}$ ) were obtained in 65–74% yields (entries 5–7). Variations of the olefin substituents as those in species **1h–1j** ( $R$ ,  $R' = \text{cyclopentyl}$ ,  $\text{cyclohexyl}$  and  $\text{dipropyl}$ ) were still compatible with these new N–O annulations to afford compounds **3h–3j** in 55–67% yields (entries 8–10). We have also prepared a terminal alkyne such as 1-ethynyl-2-styrylbenzene **1k** that gave a recovery yield (>95%) of two reactants under the standard conditions.

We next examined anthranils **2b–2f** bearing various C(5)-substituents ( $X' = \text{Me}$ ,  $\text{Cl}$ ,  $\text{Br}$ ,  $\text{OMe}$  and  $\text{OCO}_2\text{Et}$ ), yielding cyclic nitroso species **3k–3o** in 48–77% yields, with  $X' = \text{OMe}$  becoming less efficient (entries 11–15). Methoxy-containing anthranil **2e** renders the gold catalyst less reactive because of its high basicity. This gold catalysis worked well with additional anthranils **2g** and **2h** bearing C(6)-substituents ( $Y' = \text{Br}$  and  $\text{Me}$ ), yielding the desired **3p** and **3q** in 41% and 70% yields, respectively (entries 15 and 16). We also varied the C(3)-substituents of anthranils ( $R' = \text{Ph}$  **2i**;  $\text{Me}$  **2j**) to yield the desired **3r** and **3s** in 35% and 63% yields, respectively (entries 18 and 19). An effective range of alkynes and anthranils manifests the practicability of these new nitroso annulations.

This gold-catalyzed reaction was also extensible to an internal alkyne **4a**, but led to a distinct (4+3)-annulation reaction without a skeletal rearrangement. Among various gold catalysts,  $\text{P(OPh)}_3\text{AuCl}/\text{AgSbF}_6$  was superior to its  $\text{NTf}_2$  catalyst analogue, delivering a nitroso product **5a** with respective yields

of 78% and 68%; a molar ratio of **4a/2a** = 1 : 2.1 was the optimized condition. The molecular structure of **5a** was inferred from its **5b** analogue (Table 3, entry 1).<sup>9</sup>

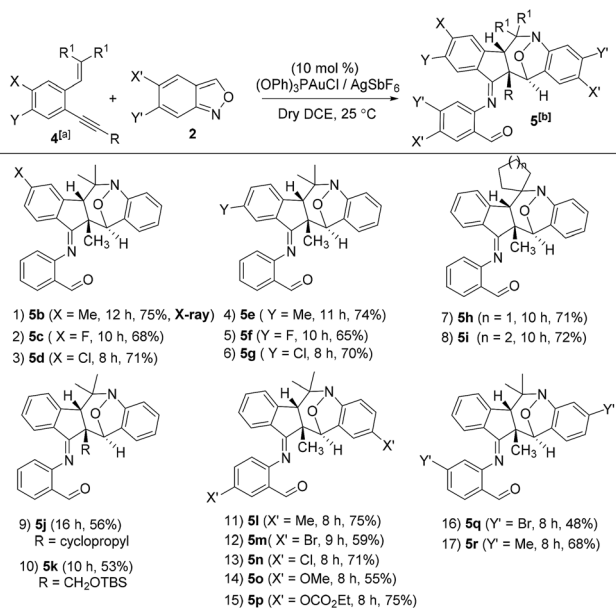


We assess the scope of these nitroso annulations with various internal 1,5-enynes **4** and anthranils **2**; only one diastereomeric product was obtained without exception. Entries 1–6 show the compatibility of these reactions with 1,5-enynes **4b–4d** and **4e–4g** bearing 4- and 5-phenyl substituents ( $X = \text{Me}$ ,  $\text{F}$  and  $\text{Cl}$  or  $Y = \text{Me}$ ,  $\text{F}$  and  $\text{Cl}$ ), delivering compounds **5b–5d** and **5e–5g** in 65–75% yields (entries 1–6). An X-ray diffraction study<sup>9</sup> confirms the molecular structure of compound **5b** showing no skeletal rearrangement. 1,5-Enynes **4h** and **4i** bearing varied trisubstituted alkenes were also suitable for the reactions, affording the desired nitroso species **5h** and **5i** in 71–72% yields (entries 7 and 8). When the alkyl substituents  $R$  were a cyclopropyl or  $\text{CH}_2\text{OTBS}$  group, the corresponding compounds **5j** and **5k** were obtained in 56% and 53% yields, respectively (entries 9 and 10). We tested the reactions of various anthranils **2b–2f** bearing various C(5)-substituents ( $X' = \text{Me}$ ,  $\text{Br}$ ,  $\text{Cl}$ ,  $\text{OMe}$  and  $\text{OCO}_2\text{Et}$ ), giving the expected products **5l–5p** in 55–75% yields with the methoxy substituent being less efficient (entries 11–15). For additional anthranils **2g** and **2h** bearing 6-substituents ( $Y' = \text{Br}$  and  $\text{Me}$ ), the resulting products **5q** and **5r** were obtained in 48% and 68% yields, respectively (entries 16 and 17).

We performed the reductive N–O cleavage of compounds **3a** and **5a** to manifest their synthetic utility. Treatment of species **3a** with  $\text{Zn}$  in  $\text{AcOH}/\text{MeOH}/\text{H}_2\text{O}$ <sup>10</sup> gave compound **6a** in 89% yield while the reaction with  $\text{Pd}/\text{H}_2$  gave compound **6b** efficiently. Alternatively, compound **5a** was hydrolyzed with  $\text{HCl}$ /water to yield ketone derivative **7b** that was convertible to 1-amino-5-ol **7c** with  $\text{Zn}/\text{AcOH}$  reduction, and to the diol derivative **7d** with  $\text{Pd}/\text{H}_2$  reduction. An imine reduction of species **5a** was achieved with  $\text{Pd}/\text{H}_2$  to afford species **7a**. Unexpectedly,  $\text{Zn}$ -reduction of species **5a** in  $\text{HOAc}/\text{MeOH}/\text{water}$  led to a structural rearrangement to form compound **7e** in 81% yield. The imine moiety of the initial **5a** was incorporated into the structural skeleton of product **7e**, but the mechanism is not clear at this stage. Molecular structures of compounds **7a** and **7e** were verified by X-ray diffraction.<sup>9</sup> The mechanism for the transformation of **5a** into **7e** will be elucidated in a future study (Scheme 1).

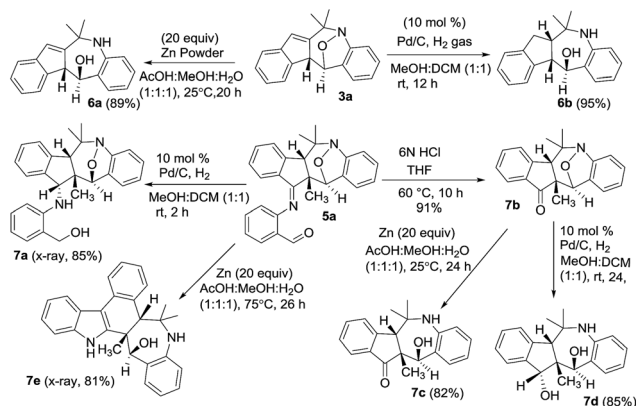
Among the two nitroso annulations, the mechanism for terminal 1,5-enynes **1a** is difficult to deduce because its cycloisomerization product **1a'** is not skeletally rearranged. We prepared  $^{13}\text{C}$ -**1a** containing 12%  $^{13}\text{C}$  at only the  $=\text{C}-\text{H}$  carbon, and its resulting product **3a** contained the  $^{13}\text{C}$ -content only at

Table 3 Reactions with internal 1,5-enynes and anthranils



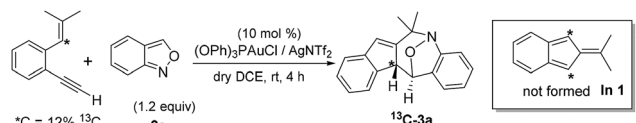
<sup>a</sup> **4/2** = 1 : 2.1, **[4]** 0.20 M. <sup>b</sup> Yields of the products were reported after isolation on a silica gel column.





Scheme 1 Reductive cleavage of the N–O bonds.

the alkyl C–H carbon (eqn (6)). Isobenzofulvene species **In 1** was unlikely to occur here although it was observed in a ruthenium-catalyzed cycloisomerization.<sup>11</sup> In the presence of D<sub>2</sub>O, we found that the resulting **d<sub>1</sub>-3a** contained deuterium ( $X = 0.29D$ ) only at its alkenyl C–H moiety (eqn (7)). Accordingly, gold-containing isobenzofulvene **In 2** is compatible with these <sup>13</sup>C and <sup>2</sup>H-labeling experiments.

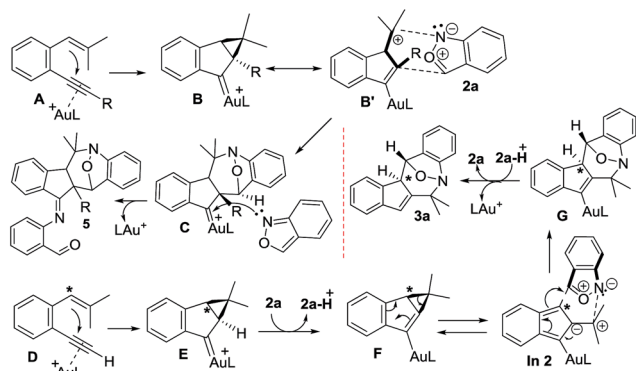


(6)

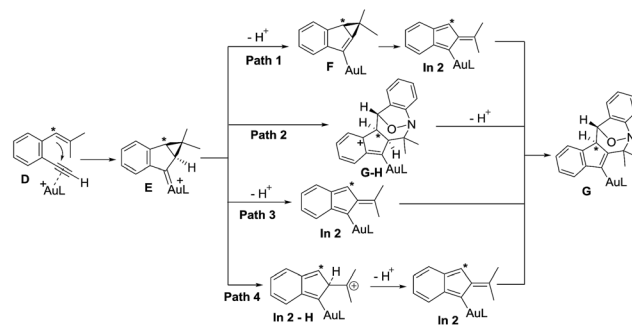


(7)

Scheme 2 depicts the mechanisms of the two annulations. Internal 1,5-enynes **4** react with LAu<sup>+</sup> to form cyclopropyl gold carbenes **B** (or **B'**) in two resonance forms; *exo*-(4+3)-



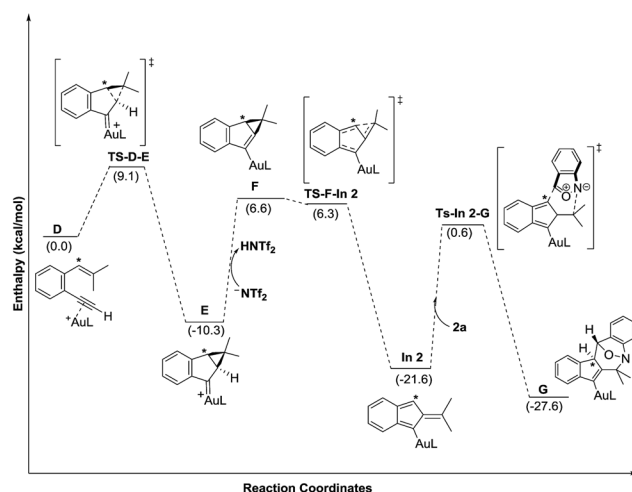
Scheme 2 Plausible mechanisms for rearrangement and non-rearrangement.



Scheme 3 Four possible paths for the D → G transformation.

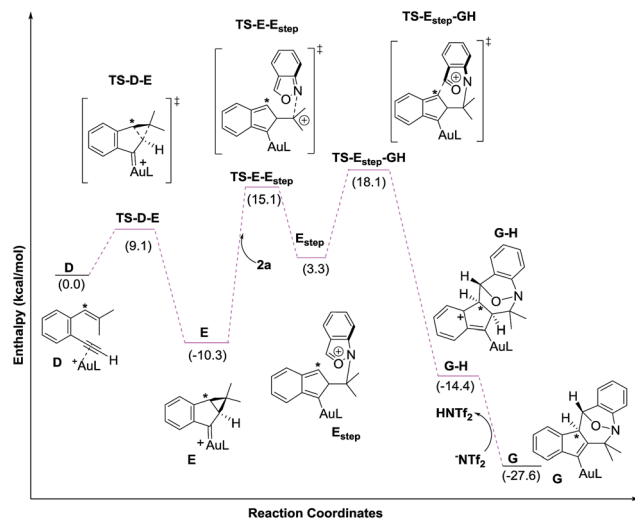
annulations of species **B'** with anthranils **2a** likely yield gold-carbene species **C** that subsequently capture a second anthranil to yield products **5**. This mechanism is essentially the same as that of their annulations with nitrosoarenes.<sup>12</sup> Herein, a stepwise mechanism for the annulation of anthranils with 1,3-dipoles **B/B'** is also likely to occur. Terminal 1,5-enyne **1a** also generates cyclopropylgold carbene **E** because its cycloisomerization product **1a'** is also a 1-vinylindene derivative. We envisage that the cyclopropyl C–H proton of gold carbene **E** is acidic because of its proximity to the gold carbene functionality; the deprotonation with anthranil **2a** generates cyclopropylidenylgold species **F** that undergoes a “methyl-enecyclopropane-trimethylenemethane” rearrangement,<sup>13</sup> further generating gold-containing isobenzofulvene species **In 2**. An *exo*-(3+4)-annulation between fulvene **In 2** and anthranil **2a** affords the observed product **3a**. The intermediacy of organogold species **G** is supported by <sup>2</sup>H and <sup>13</sup>C-labeling experiments.

Density functional theory calculations were then performed to investigate the feasibility for the key steps **D** → **G**. Four possible paths 1–4 are considered; Path 1 is our proposed mechanism in Scheme 2. The energy profile is provided in Scheme 4. The formation of cyclopropylgold carbenes **E** from  $\pi$ -alkyne **D** has a low barrier of 9.1 kcal mol<sup>−1</sup>; the anion-promoted deprotonation of gold carbene **E** to form



Scheme 4 DFT calculation and energy profiles of Path 1.





Scheme 5 DFT calculation and energy profiles of Path 2.

cyclopropylidene-gold species **F** is operable as the enthalpy cost is  $16.9 \text{ kcal mol}^{-1}$ ; the energy of species **F** is slightly higher than that of  $\pi$ -alkyne **D** by only  $6.6 \text{ kcal mol}^{-1}$ . The remaining steps **F**  $\rightarrow$  **In 2** and **In 2**  $\rightarrow$  **G** are also operable as the transition states **TS-F-In2** and **TS-In2-G** are close to  $\pi$ -alkyne **D** energy levels. One notable feature is that the enthalpy of transition state **TS-F-In2** is surprisingly smaller than that of species **F** by  $-0.3 \text{ kcal}$ . This atypical case has similar precedents in the literature.<sup>14</sup> This is because **TS-F-In2** has less zero-point vibration energy than **F**, due to the loss of one degree of freedom in the transition state. This also means that **F**  $\rightarrow$  **In2** is a barrierless process.

We next examined the energy profiles in the (4+3) annulations (Path 2) between cyclopropyl gold carbenes **E** and anthranil **2a**. The reaction proceeds in a stepwise manner. As shown in Scheme 5, the N-attack of anthranil **2a** at gold carbene **E** produces species **E<sub>step</sub>** by an endothermic process ( $H = 13.6 \text{ kcal mol}^{-1}$ ); its activation energy is as high as  $25.4 \text{ kcal mol}^{-1}$ . In the next step involving **E<sub>step</sub>**  $\rightarrow$  **GH**, the energy level of **TS-E<sub>step</sub>-GH** is higher than that of 1,5-enyne **D** by  $18.1 \text{ kcal mol}^{-1}$ . We conclude that Path 2 is not as feasible as Path 1 according to Scheme 5.

We also considered the remaining Paths 3 and 4, as depicted in Scheme 3. In Path 3, the deprotonation and ring rearrangement take place simultaneously (**E**  $\rightarrow$  **In2**), in contrast to a stepwise process in Path 1 (**E**  $\rightarrow$  **F**  $\rightarrow$  **In2**). Despite multiple attempts, we were unable to locate the transition state for the direct **E**  $\rightarrow$  **In2** step, suggesting that Path 3 probably does not exist. In Path 4, a ring opening takes place initially (**E**  $\rightarrow$  **In2-H**), followed by deprotonation (**In2-H**  $\rightarrow$  **In2**). However, our calculations show that this pathway is unlikely to occur as we are unable to locate **In2-H**; all geometry optimizations lead to **E**.

## Conclusions

Before this work, Au- and Pt-catalyzed annulations of anthranils with alkynes typically produced azacyclic products that cleaved the N-O bonds. To develop new (4+3)-annulations of alkyne-

derived 1,3-dipoles<sup>15</sup> with anthranils, we achieve stereoselective synthesis of two classes of tetrahydrobenzo[*b*]azepines using 1,5-enynes, anthranils and a gold catalyst. Internal 1,5-enynes deliver these cyclic nitroso species without skeletal rearrangement while their terminal alkyne analogues afford distinct annulation products with skeletal rearrangement. To elucidate the mechanism of this rearrangement, <sup>2</sup>H and <sup>13</sup>C-labeling experiments were performed to identify the intermediates of gold-containing isobenzofulvene species, the formation of which is dependent on the presence of anthranils.

## Conflicts of interest

There are no conflicts of interest to declare.

## Acknowledgements

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## Notes and references

- See selected reviews: (a) F. Hu and M. Szostak, *Adv. Synth. Catal.*, 2015, **357**, 2583–2614; (b) P. Vitale and A. Scilimati, *Curr. Org. Chem.*, 2013, **17**, 1986–2000; (c) A. L. Sukhorukov and S. L. Lorfe, *Chem. Rev.*, 2011, **111**, 5004–5041; (d) P. Grunanger, P. Vita-Finzi and J. E. Dowling, in *Chemistry of Heterocyclic Compounds, Part 2*, ed. E. C. Taylor and P. Wipf, Wiley, New York, 1999, vol. 49, pp. 1–888; (e) P. Pevarello, R. Amici, M. G. Brasca, M. Villa and M. Virasi, *Targets Heterocycl. Syst.*, 1999, **3**, 301–339.
- (a) S. Gómez-Ayala, J. A. Castrillón, A. Palma, S. M. Leal, P. Escobar and A. Bahsas, *Bioorg. Med. Chem.*, 2010, **18**, 4721–4739; (b) W. L. Wan, J. B. Wu, F. Lei, X. L. Li, L. Hai and Y. Wu, *Chin. Chem. Lett.*, 2012, **23**, 1343–1346; (c) O. Krebs, P. Kuenti, C. Michlig, K. Reuter, *US Pat. No.* 8,343,956 B2, 2013.
- For biological activity, see selected papers: (a) M. B. Dixon and Y. H. Lien, *Ther. Clin. Risk Manage.*, 2008, **4**, 1149–1155; (b) E. K. Miller, K. Y. Chung, J. P. Hutcheson, D. A. Yates, S. B. Smith and B. J. Johnson, *J. Anim. Sci.*, 2012, **90**, 1317–1327; (c) G. Aperis and P. Alivanis, *Rev. Recent Clin. Trials*, 2011, **6**, 177–188; (d) M. Gheorghiad, M. A. Konstam and J. C. Burnett, *JAMA, J. Am. Med. Assoc.*, 2007, **297**, 1332–1343; (e) R. W. Schrier, P. Gross and M. Gheorghiad, *N. Engl. J. Med.*, 2006, **355**, 2099–2112.
- (a) O. A. Ivanova, E. M. Budynina, Y. K. Grishin, I. V. Trushkov and P. V. Verteletskii, *Angew. Chem., Int. Ed.*, 2008, **47**, 1107–1110; (b) O. A. Ivanova, E. M. Budynina, Y. K. Grishin, I. V. Trushkov and P. V. Verteletskii, *Eur. J. Org. Chem.*, 2008, 5329–5335; (c) L. K. B. Garve, M. Pawliczek, J. Wallbaum, P. G. Jones and D. B. Werz, *Chem.-Eur. J.*, 2016, **22**, 521–525; (d) Z.-H. Wang, H.-H. Zhang, D.-M. Wang, P.-F. Xu and Y.-C. Luo, *Chem. Commun.*, 2017, **53**, 8521–8524.



- 5 See selected reviews: (a) N. De and E. J. Yoo, *ACS Catal.*, 2018, **8**, 48–58; (b) D. Garayalde and C. Nevado, *ACS Catal.*, 2012, **2**, 1462–1479; (c) D. B. Huple, S. Ghorpade and R.-S. Liu, *Adv. Synth. Catal.*, 2016, **358**, 1348–1367.
- 6 (a) A.-H. Zhou, Q. He, C. Shu, Y.-F. Yu, S. Liu, T. Zhao, W. Zhang, X. Lu and L.-W. Ye, *Chem. Sci.*, 2015, **6**, 1265–1271; (b) X.-Y. Xiao, A.-H. Zhou, C. Shu, F. Pan, T. Li and L.-W. Ye, *Chem.-Asian J.*, 2015, **10**, 1854–1858; (c) R. L. Sahani and R.-S. Liu, *Angew. Chem., Int. Ed.*, 2017, **56**, 1026–1030; (d) W.-B. Shen, X.-Y. Xiao, Q. Sun, B. Zhou, X.-Q. Zhu, J.-Z. Yan, X. Lu and L.-W. Ye, *Angew. Chem., Int. Ed.*, 2017, **56**, 605–609; (e) S. S. Giri and R.-S. Liu, *Chem. Sci.*, 2018, **9**, 2991–2995; (f) L. Li, T.-D. Tan, Y.-Q. Zhang, X. Liu and L.-W. Ye, *Org. Biomol. Chem.*, 2017, **15**, 8483–8492.
- 7 (a) H. Jin, L. Huang, J. Xie, M. Rudolph, F. Rominger and A. S. K. Hashmi, *Angew. Chem., Int. Ed.*, 2016, **55**, 794–797; (b) H. Jin, B. Tian, X. Song, J. Xie, M. Rudolph, F. Rominger and A. S. K. Hashmi, *Angew. Chem., Int. Ed.*, 2016, **55**, 12688–12692; (c) R. L. Sahani and R.-S. Liu, *Angew. Chem., Int. Ed.*, 2017, **56**, 12736–12740; (d) B. D. Mokal, P. D. Jadhav, Y. B. Pandit and R.-S. Liu, *Chem. Sci.*, 2018, **9**, 4488–4492.
- 8 For gold-catalyzed enyne cycloisomerizations, see: (a) R. Dorel and A. M. Echavarren, *Chem. Rev.*, 2015, **115**, 9028–9072; (b) E. J. Núñez and A. M. Echavarren, *Chem. Rev.*, 2008, **108**, 3326–3350; (c) A. S. K. Hashmi and M. Rudolph, *Chem. Soc. Rev.*, 2008, **37**, 1766–1775; (d) A. Fürstner and P. W. Davies, *Angew. Chem., Int. Ed.*, 2007, **46**, 3410–3449; (e) L. Zhang, J. Sun and S. A. Kozmin, *Adv. Synth. Catal.*, 2006, **348**, 2271–2296.
- 9 Crystallographic data of compounds **3a**, **5b**, **7a** and **7e** were deposited at the Cambridge Crystallographic Center; **3a**, CCDC 1853703; **5b**, CCDC 1853704; **7a**, CCDC 1853705 and **7e**, CCDC 1853706.†
- 10 (a) R. K. Kawade and R.-S. Liu, *Angew. Chem., Int. Ed.*, 2017, **56**, 2035–2039; (b) P. Sharma, P. D. Jadhav, M. Skaria and R.-S. Liu, *Org. Biomol. Chem.*, 2017, **15**, 9389–9397.
- 11 Isobenzofulvene In was the intermediate in the cycloisomerization of terminal 1,5-enyne **1a** involving ruthenium vinylidene as the initial species. See: R. J. Madhushaw, C.-Y. Lo, C.-W. Hwang, M.-D. Su, H.-C. Shen, S. Pal, I. R. Shaikh and R.-S. Liu, *J. Am. Chem. Soc.*, 2004, **126**, 15560–15565.
- 12 For 1,*n*-enynes as 1,*n*-dipoles, see: (a) C.-H. Chen, Y.-C. Tsai and R.-S. Liu, *Angew. Chem., Int. Ed.*, 2013, **52**, 4599–4603; (b) S. A. Gawade, S. Bhunia and R.-S. Liu, *Angew. Chem., Int. Ed.*, 2012, **51**, 7835–7838; (c) A. Escibano-Cuesta, V. Lopez-Carrillo, D. Janssen and A. M. Echavarren, *Chem.-Eur. J.*, 2009, **15**, 5646–5650; (d) D. B. Huple and R.-S. Liu, *Chem. Commun.*, 2012, **48**, 10975–10977.
- 13 (a) M. Rule, R. F. Salinaro, D. R. Pratt and J. A. Berson, *J. Am. Chem. Soc.*, 1982, **104**, 2223–2228; (b) R. F. Salinaro and J. A. Berson, *J. Am. Chem. Soc.*, 1982, **104**, 2228–2232.
- 14 (a) S. Wolfe, S. Hoz, C. K. Kim and K. Y. Yang, *J. Am. Chem. Soc.*, 1990, **112**, 4186–4191; (b) W. C. Chen and C. H. Yu, *Chem. Phys. Lett.*, 1997, **277**, 245–251; (c) H. F. Su, R. I. Kaiser and A. H. H. Chang, *J. Chem. Phys.*, 2005, **122**, 074320.
- 15 For Au-containing all-carbon 1,3-dipoles, see selected examples: (a) G. Zhang and L. Zhang, *J. Am. Chem. Soc.*, 2008, **130**, 12598–12599; (b) X. Huang and L. Zhang, *J. Am. Chem. Soc.*, 2007, **129**, 6398–6399; (c) M. Schelweis, A. L. Dempwolff, F. Rominger and G. Helmchen, *Angew. Chem., Int. Ed.*, 2007, **46**, 5598–5601; (d) T.-M. Teng, A. Das, D. B. Huple and R.-S. Liu, *J. Am. Chem. Soc.*, 2010, **132**, 12565–12567; (e) T.-M. Teng and R.-S. Liu, *J. Am. Chem. Soc.*, 2010, **132**, 9298–9300.

