DOI: 10.1002/chem.201000009

# Construction of 2,3-Dihydrofuran Cores through the [3+2] Cycloaddition of Gold α-Carbonylcarbenoids with Alkenes

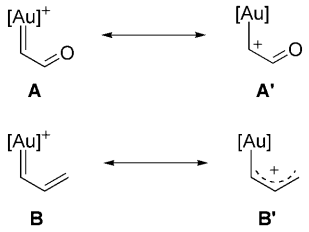
**Chia-Wen Li, Guan-You Lin, and Rai-Shung Liu*[a]**

**Abstract:** Treatment of 2-epoxy-1-alkynylbenzenes with electron-rich alkenes and a $[AuCl(PR_3)]/AgX$ catalyst in $CH_2Cl_2$ led to the formation of 2-alkenyl-1-(2,3-dihydrofuran-4-yl)benzenes. This transformation comprises of a gold-catalyzed redox reaction to form a gold α-carbonylcarbenoid initially, which then reacts in situ with an alkene in a [3+2] cycloaddition. A range of alkenes are amenable to this tandem reaction, amongst them α-substituted styrenes, enol ethers, and 2,3-dimethylbutadienes. Deuterium-labeling experiments suggest a stepwise mechanism for the α-carbonylcarbenoid/alkene [3+2] cycloaddition. The resulting 2,3-dihydrofuran products allow access to diverse oxacyclic compounds through a stereoselective ene–oxonium reaction initiated by treatment with HOTf (1 mol%; Tf = trifluoromethanesulfonyl). A stepwise pathway is proposed for this reaction. The feasibility for direct transformation of 2-alkenyl-1-alkynylbenzenes into the desired 2,3-dihydrofuran products through initial *m*-chloroperbenzoic acid oxidation, followed by the addition of gold catalyst and alkene, has also been demonstrated.

**Keywords:** cycloaddition · dihydrofurans · carbenoids · epoxides · gold

## Introduction

One important advent in modern synthetic chemistry is the generation of a metal carbenoid from an alkyne using $Au^I$ catalysts.[1–5] Among the reported gold carbenoids, the α-carbonylcarbenoid is the most easily accessible because of the availability of various redox reactions for carbenoid generation.[2–4] However, the use of gold α-carbonylcarbenoid **A** is less widespread than that of gold alkenylcarbenoid **B**,[6–8] indicated by its lack of cycloaddition reactions. Alkenylcarbenoid **B** is also represented by the gold-stabilized allyl cation **B′** to rationalize its highly electrophilic nature[6,7] and versatile [3+*n*] (*n* = 2, 3, or 4) cycloaddition reactions.[8] In contrast, gold α-carbonylcarbenoid **A** truly reflects a carbenoid character because the resonance structure **A′** is less important (Scheme 1).




Scheme 1. Representations for α-carbonylcarbenoid **A** and alkenylcarbenoid **B**.

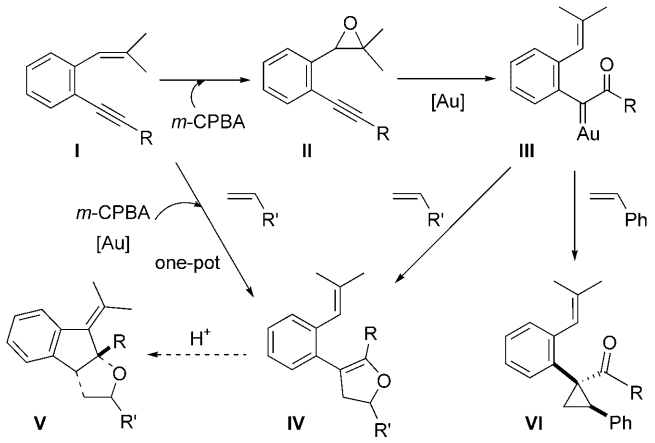
Cycloaddition of gold α-carbonylcarbenoids with dipolarophiles remains a formidable obstacle to overcome. Although the [3+2] cycloaddition of α-carbonylcarbenoids with alkenes was documented for copper and rhodium systems from α-diazocarbonyl precursors, reported examples are limited strictly to reactions with enol ethers.[9] For gold alkenylcarbenoids **B**, reactions with alkenes or enol ethers gave only cyclopropane products.[10,11]

Recently, Hashmi et al.[4b] and ourselves[4a] independently studied the cycloisomerization of 2-epoxy-1-alkynylbenzenes **II** (Scheme 2) using different gold catalysts. Notably, the use of $[AuCl(PPh_3)]/AgSbF_6$ (each at 5 mol% loading) led to the epoxide/ketone rearrangement of starting substrate **II**. With $[AuCl(PPh_3)]/AgSbF_6$ (5 and 2 mol%, respectively) we found that the resulting carbenoids **III** were stable and efficiently trapped with an external styrene or $Ph_2SO$, as depicted in Scheme 2.[5a] The tethered alkene in **III** does not affect the carbenoid electrophilicity and the species retains activity

[a] C.-W. Li, Dr. G.-Y. Lin, Prof. Dr. R.-S. Liu
Department of Chemistry, National Tsing-Hua University
Hsinchu, Taiwan (ROC)
Fax: (+86) 3-5711082
E-mail: rsliu@mx.nthu.edu.tw

Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/chem.201000009.



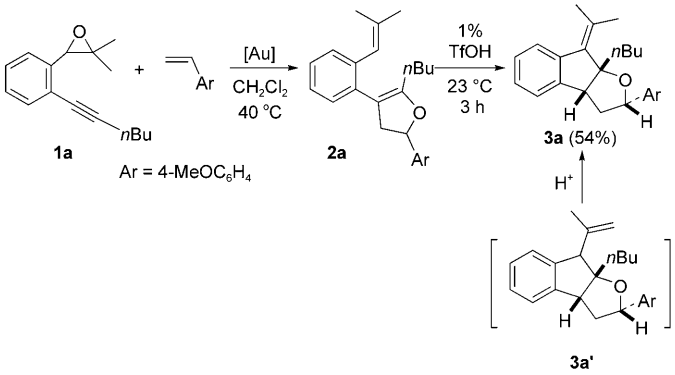

Scheme 2. Reaction pathways in this gold catalysis.

toward external nucleophiles. This pathway is distinct from that reported by Hashmi and co-workers for carbonyldienyl gold carbenoids.[5g] The gold carbenoids generated from sulfur- and nitrogen-based redox reactions inevitably suffer loss of electrophilicity through heteroatom coordination. The use of these carbenoids is strictly limited to cyclization with their tethered functionalities.[2–4] Herein, we report the [3+2] cycloaddition reactions of gold α-carbonylcarbenoids **III** with a range of alkenes. We also report that the resultant 2,3-dihydrofurans **IV** undergo a subsequent HOTf-catalyzed (Tf = trifluoromethanesulfonyl) cyclization to give tricyclic tetrahydrofuran species **V** and other oxacyclic compounds with high stereocontrol. We also demonstrate examples for a one-pot transformation of 2-alkenyl-1-alkynylbenzenes **I** and alkenes into 2,3-dihydrofurans **IV** through gold-catalyzed oxidation with *m*-chloroperbenzoic acid (*m*-CPBA). This direct synthesis uses *m*-CPBA as a source of oxygen to generate α-carbonylcarbenoid **III** (Scheme 2).

## Results and Discussion

Generation of α-carbonylcarbenoid **III** from epoxide **II** was previously performed with a mixture of $[AuCl(PPh_3)]$ (5 mol%)/$AgSbF_6$ (2 mol%),[12a] which completely inhibited the competitive epoxy–ketone rearrangement.[5a] As depicted in Table 1, this catalyst mixture implemented the cyclization of epoxide species **1a** with 4-vinyl-1-methoxybenzene (5 equiv) in $CH_2Cl_2$ (40 °C, 6 h) to give the desired 2,3-dihydrofuran **2a** in 64% yield. Modification of the catalyst with $[AuCl\{P(o\text{-biphenyl})(t\text{Bu})_2\}]$ or $AgNTf_2$ failed to result in any improvement (Table 1, entries 2 and 3). The selection of a suitable catalyst is sensitive to the alkene substrate. The combination of $[AuCl\{P(o\text{-biphenyl})(t\text{Bu})_2\}]/AgNTf_2$[12b] was superior to $[AuCl(PPh_3)]/AgSbF_6$ when an enol ether was used (see below).[13] Subsequent treatment of compound **2a** with HOTf (1 mol%) in $CH_2Cl_2$ (23 °C, 3 h) led to an intramolecular cyclization and gave tricyclic ether **3a** in 54% yield. At 40% conversion in $CH_2Cl_2$ (23 °C, 1 h), we observed that the isomeric product **3a′** (15%) was formed

Table 1. Screening of catalyst activity.



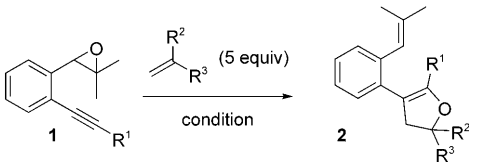

| Entry | Catalyst[a] | *t* [h] | Yield of **2a** [%][b] |
|---|---|---|---|
| 1 | 5% $[AuCl(PPh_3)]$<br>2% $AgSbF_6$ | 6 | 64 |
| 2 | 5% [AuClL][c]<br>2% $AgNTf_2$ | 6 | 54 |
| 3 | 5% $[AuCl(PPh_3)]$<br>2% $AgNTf_2$ | 10 | 12 |

[a] [**1a**] = 0.1 M, alkene (5 equiv), $CH_2Cl_2$. [b] Yields are reported after silica chromatography. [c] [AuClL] = $[AuCl\{P(t\text{Bu})_2(o\text{-biphenyl})\}]$.

along with species **3a** (21%). Species **3a′** quickly isomerized to the more stable isomer **3a** after a short reaction catalyzed by Brønsted acid. Isolation of isomer **3a′** in a pure form was hampered by its instability during elution on a silica column, but it was identified by $^1H$ NMR spectroscopy.

The generality of this 2,3-dihydrofuran synthesis using various alkenes and epoxides was assessed (Table 2). We used three different catalysts to optimize the yields: [AuCl-

Table 2. Gold-catalyzed [3+2] cycloadditions.




| Entry | Epoxide $R^1$ | $R^2$ | Alkene $R^3$ | Conditions[a] (*t* [h]) | Products[b] (yield [%]) |
|---|---|---|---|---|---|
| 1 | *n*Bu (**1a**) | Me | 4-$MeOC_6H_4$ | B (6) | **2b** (95) |
| 2 | *n*Bu (**1a**) | Me | Ph | A (6) | **2c** (82) |
| 3 | *n*Bu (**1a**) | *n*Bu | Ph | A (6) | **2d** (52) |
| 4 | *n*Bu (**1a**) | Me | 2-naphthyl | A (6) | **2e** (50) |
| 5 | *n*Bu (**1a**) | Ph | Ph | A (6) | **2f** (78) |
| 6 | *n*Bu (**1a**) | H | OEt | B (3) | **2g** (88) |
| 7 | *n*Bu (**1a**) | Me | OMe | B (6) | **2h** (78) |
| 8 | *n*Bu (**1a**) | Me | −CMe(C=$CH_2$) | C (12) | **2i** (51) |
| 9 | Ph (**1b**) | H | OEt | B (12) | **2j** (81) |
| 10 | Ph (**1b**) | H | 4-$MeOC_6H_4$ | A (12) | **2k** (68)[c] |
| 11 | Ph (**1b**) | Me | Ph | A (12) | **2l** (61) |
| 12 | Me (**1c**) | Me | Ph | A (6) | **2m** (56) |
| 13 | Me (**1c**) | H | OEt | B (3) | **2n** (65) |

[a] A: $[AuCl(PPh_3)]$ (5%), $AgSbF_6$ (2%), $CH_2Cl_2$, 40 °C; B: $[AuCl\{P(t\text{Bu})_2(o\text{-biphenyl})\}]$ (5%), $AgNTf_2$ (2%), $CH_2Cl_2$, 40 °C; C: $[AuCl(IPr)]$ (5%), $AgSbF_6$ (2%), [epoxide] = 0.1 M, $CH_2Cl_2$, 40 °C. [b] Yields are reported after separation on a silica column. [c] Cyclopropanation product was obtained in 14% yield.[19]

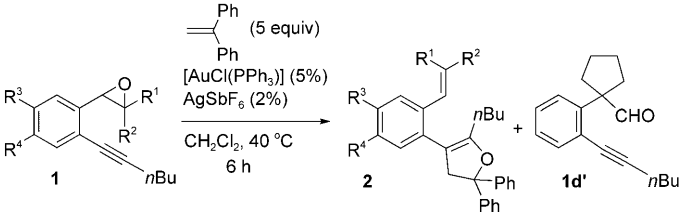
  

$(PPh_3)]/AgSbF_6$ (**A**), $[AuCl\{P(o\text{-biphenyl})(t\text{Bu})_2\}]/AgNTf_2$ (**B**), and $[AuCl(IPr)]/AgSbF_6$[12c] (**C**, IPr = 1,3-bis(diisopropylphenyl)imidazol-2-ylidene), all with an $Au^I/Ag^I$ ration of 5:2 mol%. These systems were applied to derivatives of styrenes, enol ethers, and 2,3-dimethylbutadiene, respectively.

Table 2, entries 1–5, shows the effect of α-substitution on the styrene. Alkenes with $R^2$ = methyl or phenyl (Table 2, entries 2 and 5) gave better yields than the $R^2 = n$-butyl analogue (Table 2, entry 3). The alkene in which $R^3$ = 2-naphthyl is an inferior reaction partner to the analogues in which $R^3$ = 4-methoxyphenyl or phenyl (50% **2e** versus 95 and 82% **2b** and **2c**, respectively). Steric effects clearly affect the cycloaddition. The suitability of mono- and disubstituted enol ethers as nucleophiles was within our expectations (Table 2, entries 6 and 7) and furnished 2,3-dihydrofurans **2g** and **2h** in 88 and 78% yield, respectively. The cycloaddition is also successful with 2,3-dimethylbutadiene and gives **2i** in 51% yield (Table 2, entry 8). Table 2, entries 9–13, shows varied alkynyl substitution ($R^1$ = Ph, Me) of the epoxide substrates. Compounds **1b** and **1c** reacted with suitable styrene derivatives and enol ethers to give the desired [3+2] cycloadducts **2j**–**2n** in 56–81% yield. Alongside adduct **2k**, we obtained the cyclopropanation product in 14% yield (Table 2, entry 10).

Table 3 shows the effect of substitution of epoxy and phenyl moieties on the gold-catalyzed cycloaddition. For epoxides **1d** and **1e** the reaction with α-phenylstyrene afford-

Table 3. Effect of epoxide and phenyl substituents on the cycloaddition.



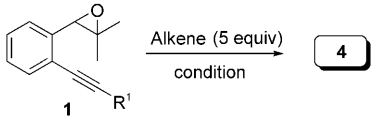

| Entry | Epoxide[a] | Products (yield [%])[b] |
|---|---|---|
| 1 | $R^1, R^2 = -(CH_2)_4-$, $R^3 = R^4 = H$ (**1d**) | **2o** (41), **1d′** (45) |
| 2 | $R^1$ = Me, $R^2$ = Et, $R^3 = R^4 = H$ (**1e**)[c] | **2p** (62, *Z*/*E* 1:1.9) |
| 3 | $R^1 = R^2$ = Me, $R^3$ = H, $R^4$ = Cl (**1f**) | **2q** (76) |
| 4 | $R^1 = R^2$ = Me, $R^3$ = H, $R^4$ = F (**1g**) | **2r** (49) |
| 5 | $R^1 = R^2$ = Me, $R^3$ = Cl, $R^4$ = H (**1h**) | **2s** (73) |
| 6 | $R^1 = R^2$ = Me, $R^3$ = F, $R^4$ = H (**1i**) | **2t** (57) |

[a] [substrate] = 0.1 M. [b] Yields are reported after separation on a silica column. [c] *Z*/*E* ratio = 1:1.2.

ed the desired 2,3-dihydrofurans **2o** and **2p** in 41 and 62% yield, respectively(Table 3, entries 1 and 2). In the former case, we also obtained aldehyde **1d′** (45%), generated from epoxide–carbonyl rearrangement.[5a] The catalysis is compatible with the presence of fluoro and chloro groups at the C4 and C5 carbon atoms of the phenyl group of the cyclization substrate (**1f**–**i**) and **2q**–**t** were obtained in 49–76% yield (Table 3, entries 3–6). The chloride substituent resulted in the most productive yield. Epoxides with electron-donating methoxy groups at the same carbon atoms failed to give the desired 2,3-dihydrofurans in tractable amounts.[14]

Table 4 highlights the use of cycloalkenes to access complex oxacyclic molecules with effective control of the stereochemistry. Treatment of epoxides **1a** and **1c** with 2,3-dihy-

Table 4. Cycloadditions of epoxides **1** with cycloalkenes.



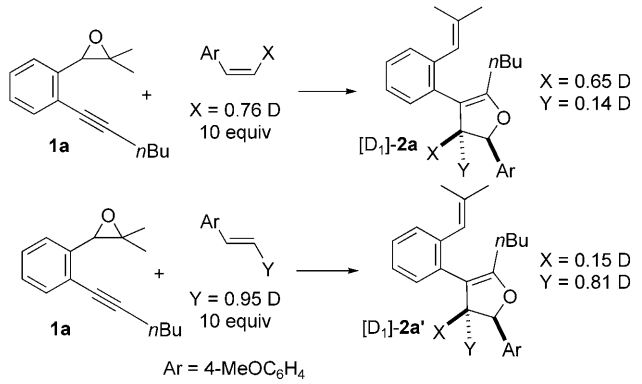

| Entry | Epoxide $R^1$ | Alkene | Conditions[a] (*t* [h]) | Products | Products (yield [%])[b] |
|---|---|---|---|---|---|
| 1 | *n*Bu (**1a**) | | | | **4a** (65) |
| 2 | Me (**1c**) | | B (3) | | **4b** (52) |
| 3 | *n*Bu (**1a**) | | | | **4c** (72) |
| 4 | Me (**1c**) | | B (3) | | **4d** (70) |
| 5 | *n*Bu (**1a**) | | A (6) | | **4e** (82) |

[a] A: $[AuCl(PPh_3)]$ (5%), $AgSbF_6$ (2%), $CH_2Cl_2$, 40°C; B: $[AuCl\{P(t\text{Bu})_2(o\text{-biphenyl})\}]$ (5%), $AgNTf_2$ (2%), $CH_2Cl_2$, 40°C. [b] Isolated yield.

drofuran or 3,4-dihydro-2*H*-pyran in the presence of $[AuCl\{P(o\text{-biphenyl})(t\text{Bu})_2\}]$ (5 mol%)/$AgNTf_2$ (2 mol%) in hot dichloromethane (conditions B) produced furans **4a** and **4b** (Table 4, entries 1 and 2) and pyrans **4c** and **4d** (Table 4, entries 3 and 4), respectively. For all these products, we obtained a single diastereomer and structural characterization relied on NOE spectroscopy of **4a** and **4d**.[15] Cycloaddition of epoxide **1a** with 1-methylene-tetrahydronaphthalene gave the desired spiroether **4e** in 82% yield (Table 4, entry 5).

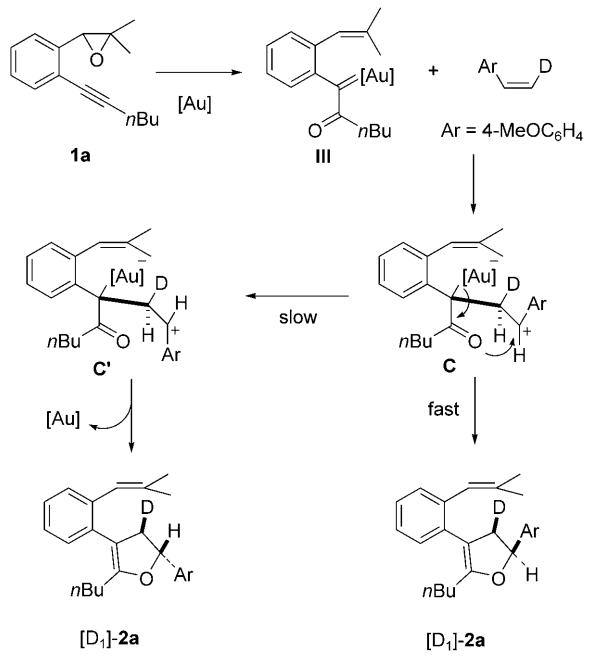
We performed deuterium-labeling experiments to understand the mechanism of the [3+2] cycloaddition reaction. As depicted in Scheme 3, treatment of epoxide **1a** with *cis*-deuterated 4-vinyl-1-methoxybenzene[16] (X = 0.76 D) gave $[D_1]$**2a**, $^1$H NMR spectroscopy of which revealed 65 and 14% deuterium content at the *cis*- and *trans*-C(3)-dihydrofuranyl hydrogen atoms, respectively. We conducted a similar experiment with the *trans*-deuterated alkene[17] (Y = 0.95 D). The resultant adduct $[D_1]$**2a′** contained 15 and 81% deuterium content at the corresponding *cis*- and *trans*-C(3)-hydrogen atoms, respectively. In both cases, a small portion of deuterium was scrambled at the other geminal hydrogen.




Scheme 3. Deuterium-labeling experiment.

Lewis acid catalyzed cycloisomerization of cyclopropyl ketones to 2,3-dihydrofurans is only operable for certain substrates[9a,18] and our control experiment opposes intermediacy of cyclopropyl ketones.[19] For starting species **1a**, we also exclude a concerted [3+2] mechanism because [D$_1$]**2a** contains deuterium at both geminal methylene positions, but in unequal proportions. This observation leads us to propose a cationic intermediate **C** that undergoes a rapid ring closure to give species [D$_1$]**2a**, with the deuterium *cis* to the neighboring aryl group. A small portion of species **C** undergoes a slow rotation of the C–C bond to give [D$_1$]**2a** with the deuterium *trans* to the aryl group after ring closure (Scheme 4). This proposed mechanism provides a rationale for the *trans*-fused stereochemistry of products **4c** and **4d** (Table 4, entries 3 and 4). This stepwise pathway may indicate that the α-carbonyl carbene is not entirely represented by structure

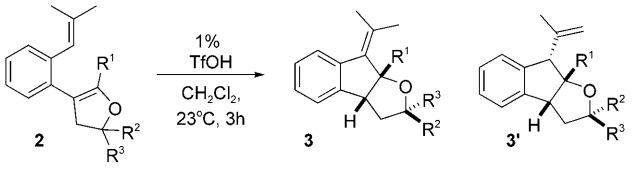



Scheme 4. Proposed mechanism of the [3+2] cycloaddition.

**A** and the contribution of the resonance structure **A′** is also significant (Scheme 1).

Table 5 highlights the use of the [3+2] cycloadducts to construct complex molecular frameworks through a HOTf-catalyzed cyclization. A small proportion of HOTf (0.1–

Table 5. HOTf-catalyzed cyclization.




| Entry | Dihydrofuran[a] R$^1$ | R$^2$ | R$^3$ | Product (yield [%])[b] | Diastereomeric ratio |
|---|---|---|---|---|---|
| 1 | *n*Bu | Me | Ph (**2c**) | **3c** (65) | 9:2 |
| 2 | *n*Bu | *n*Bu | Ph (**2d**) | **3d** (79) | 13:1 |
| 3 | *n*Bu | Me | naphthyl (**2e**) | **3e** (61) | 3:1 |
| 4 | *n*Bu | Ph | Ph (**2f**) | **3f** (87) | – |
| 5 | Ph | Me | Ph (**2l**) | **3l** (83) | 12:1 |
| 6 | *n*Bu | Me | 4-MeOC$_6$H$_4$ (**2b**) | **3b′** (62) | >20:1 |
| 7 | *n*Bu | Me | (**2i**) | **3i′** (71)[c] | >20:1 |

[a] [substrate] = 0.1 M in $CH_2Cl_2$. [b] Yields are reported after purification on a silica column. [c] 0.1 % HOTf was used for entry 7.

1 mol %), which acts a Brønsted acid, induces the formation of a cyclopentane ring in a stereoselective ene–oxonium reaction. For substrates **2c–f** and **2l**, the resulting cyclization products **3c–f** and **3l**, which contain a cyclopentylidene ring, are produced stereoselectively in most cases. Unexpectedly, we obtained cyclization products **3b′** and **3i′**, which bore a methylvinyl group, from HOTf treatment of **2b** and **2i**. The stereochemistry of cyclized products **3c**, **3b′**, and **3i′** was determined by NOE spectroscopy. Notably, we found that the stereochemistry at the *C*R$^2$R$^3$ carbon atom of **3b′** and **3i′** are opposite to those of cyclopentylidene compounds **3a**, **3c**, and **3l**. The X-ray structure of compound **3l** was also determined (see Figure 1).

We also performed HOTf-catalyzed carbocyclization of 2,3-dihydrofurans **2o–t**, which bore distinct alkenyl (R$^1$ and R$^2$) and phenyl (R$^3$ and R$^4$) substituents, and obtained the desired cyclized products **3o–t** in good yields (79–84 %, Table 6). These yields are similar to that obtained for **3f** (87 %) and thus, the reaction does not appear to be sensitive to these particular substituents.

Scheme 5 depicts a plausible mechanism to rationalize the generation of **3b′** and **3c** from cyclization of **2b** and **2c**, respectively. The differing stereochemistry at the *C*H$_3$Ar carbon for the two resulting products is clearly a crucial factor. Most likely, protonation proceeds initially on the face opposite the aryl fragment. We envisage that the oxonium cation **D** derived from **2b** is prone to epimerization to give species **D″** because the hypothetical cation **D′** is stabilized by the 4-methoxyphenyl group. Intermediate **D** is responsible for generation of cyclopentylidene **3c**, and its isomer **3c′**, through the loss of a proton from tertiary cation **E**. For species **2b**, we envisage that conformation **D″** is at-

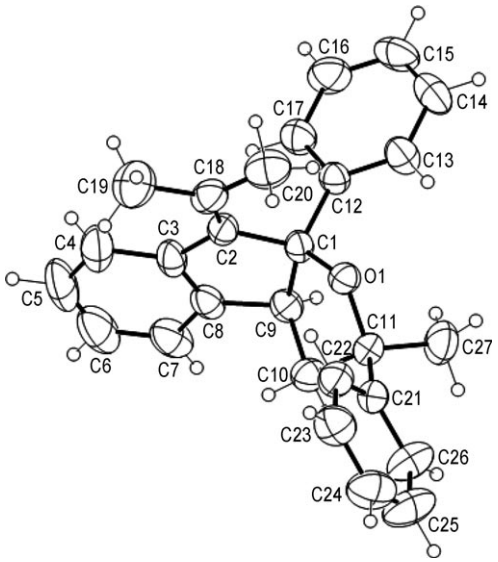
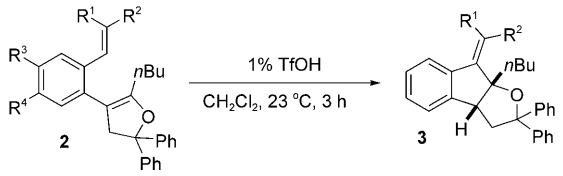



Figure 1. X-ray structure of **3l**.

tainable because the concerted ene–oxonium reaction[20] occurs on the same side as the smaller methyl group.[20] This concerted pathway is unlikely for substrate **2c** because the *endo*-phenyl orientation impedes this concerted process.

The use of this gold catalysis is enhanced by the diversity of the oxacyclic products for which only one diastereomeric compound was obtained, as illustrated in Table 7. Treatment of 2,3-dihydrofuranyl acetals **2g**, **2j**, and **2n** with HOTf (1 mol%) in $CH_2Cl_2$ (23 °C, 3 h) delivered tricyclic oxacyclic compounds **5a–5c** (Table 7, entries 1–3) in fair to good yields (52–90%). We elucidated their structures based on comparison to the $^1$H NMR spectra of oxacyclic products **3b′** and **3i′**, given from a concerted ene–oxonium reaction.[17] A diagnostic $^1$H NMR signal for such a structural assignment is the observed coupling constant of $J = 4.0$ Hz between the olefin and its vicinal protons. This proposed structure was confirmed with the NOE spectra of **5c** and its sequential proton decoupling. In contrast, reaction of furan species **4a** and **4b** stereoselectively delivered oxacyclic compounds **6a** and **6b** (Table 7, entries 4 and 5). The stereochemistry of **6b** was elucidated with the aid of NOE spectroscopy. For tetrahydro-3a*H*-furo[2,3-*b*]pyrans **4c** and **4d** we obtained oxacyclic compounds **7a** and **7b** as single diastereomers after HOTf treatment. The NOE spectra of **7b** revealed a fully *cis*-fused configuration for its tetracyclic framework. The large bicyclic framework of species **4c** and **4d** greatly favors the conformation of oxonium species **D** to give the observed cyclopentylidene products **7a** and **7b**.

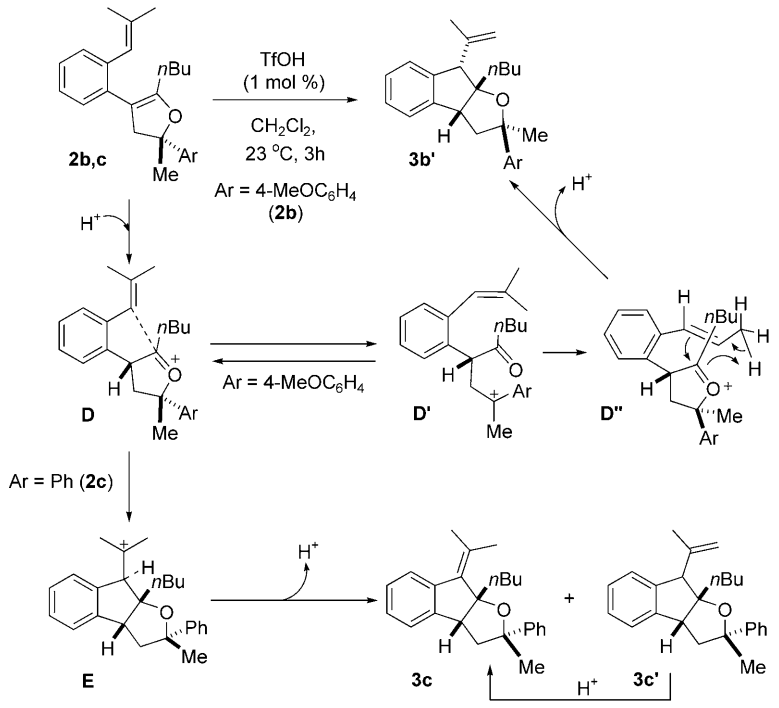
Table 6. Effect of epoxide and phenyl substituents on HOTf-catalyzed cyclization.




| Entry | Substrate[a] | Product (Yield [%])[b] |
|---|---|---|
| 1 | $R^1=R^2=$-$(CH_2)_4$-, $R^3=R^4=$H (**2o**) | **3o** (79) |
| 2 | $R^1=$Me, $R^2=$Et, $R^3=R^4=$H (**2p**) | **3p** (79) |
| 3 | $R^1=R^2=$Me, $R^3=$H, $R^4=$Cl (**2q**) | **3q** (81) |
| 4 | $R^1=R^2=$Me, $R^3=$H, $R^4=$F (**2r**) | **3r** (84) |
| 5 | $R^1=R^2=$Me, $R^3=$Cl, $R^4=$H (**2s**) | **3s** (80) |
| 6 | $R^1=R^2=$Me, $R^3=$F, $R^4=$H (**2t**) | **3t** (83) |

[a] [epoxide] = 0.1 M. [b] Yields are reported after separation on a silica column.

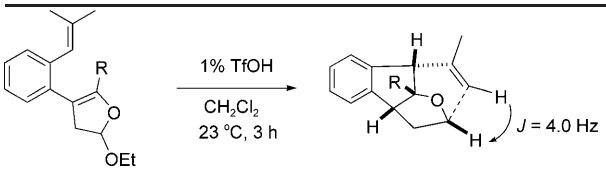
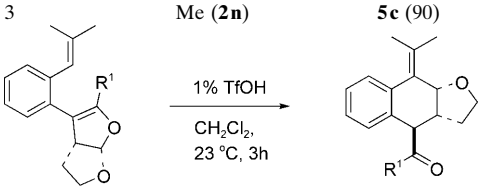
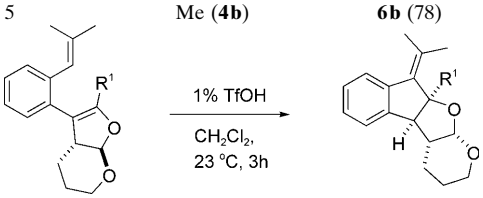
Scheme 6 depicts a plausible mechanism to rationalize the formation of the complex oxacyclic species **5c** from **2n**. The mechanism involves a concerted ene–oxonium reaction via a species of type **D″** to give intermediate **3n′**, which contains a methylvinyl group. The stereochemistry of species **3n′** is suitable for a second carbocyclization via formation of oxonium intermediate **F** to induce a second ene–oxonium reaction to give observed compound **5c**.



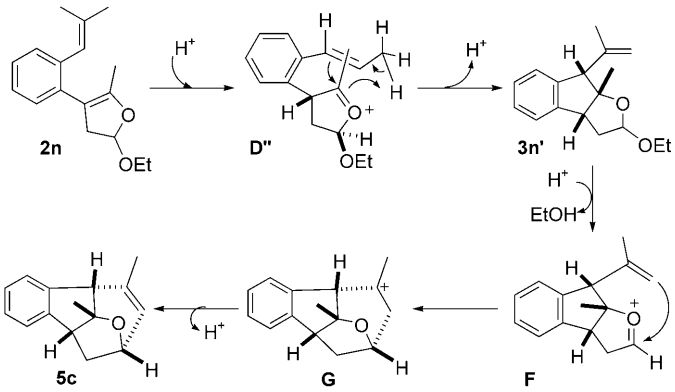

Scheme 5. Proposed mechanism of HOTf-catalyzed cyclization.

Table 7. Diverse oxacyclic products from HOTf-catalyzed cyclization.

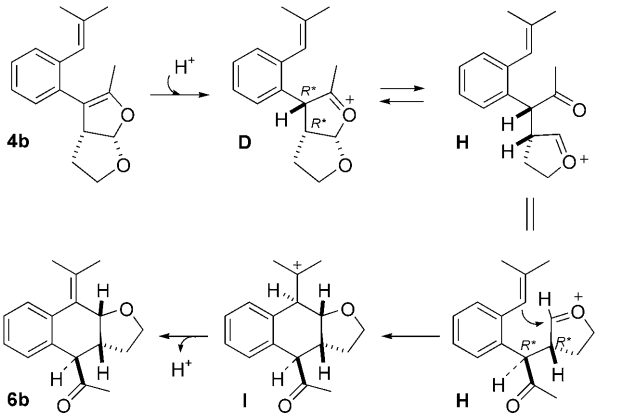
| Entry | R[a] | Product (Yield [%])[b] |
|---|---|---|
|  | | |
| 1 | *n*Bu (**2g**) | **5a** (89) |
| 2 | Ph (**2j**) | **5b** (52) |
| 3 | Me (**2n**) | **5c** (90) |
|  | | |
| 4 | *n*Bu (**4a**) | **6a** (71) |
| 5 | Me (**4b**) | **6b** (78) |
|  | | |
| 6 | *n*Bu (**4c**) | **7a** (79) |
| 7 | Me (**4d**) | **7b** (79) |

[a] [substrate] = 0.1 M. [b] Yields are reported after silica-gel column chromatography.



Scheme 6. Proposed mechanism for the formation of oxacyclic compound **5c**.

Scheme 7 illustrates the mechanism of formation of **6b** from **4b**. Protonation at the 2,3-dihydrofuranyl C(3)-carbon of **4b** preferentially proceeds on the face opposite the neighboring oxacyclic ring, which produces oxonium species **D** with a *3R*,4R** configuration. We envisage that the *cis*-2-oxabicyclo[3.3.0]octane ring of oxonium species **D** is highly strained and that this strain is sufficient to cause ring cleavage to produce a ketone–oxonium species **H**. Ultimately, species **H** gives compound **6b** through an stepwise ene–oxonium reaction. For starting substrates **4a–d**, their corresponding intermediates **D** have sterically congested and



Scheme 7. Proposed mechanism for the formation of compound **6b**.

rigid structures, which are not favorable for an initial concerted ene–oxonium reaction. These substrates will not produce complicated cage structures as seen with **5a–c**.

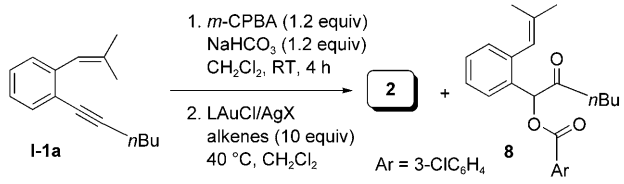
Table 8 depicts examples for the direct conversion of enyne **I-1a** to various 2,3-dihydrofurans through initial treatment with a mixture of *m*-CPBA and $NaHCO_3$ in $CH_2Cl_2$ (4 h, 25 °C), followed by the subsequent addition of a suitable alkene (10 equiv) and $Au^I/Ag^I$ catalyst (5 and 2 mol %) before the temperature was brought to 40 °C. In this one-pot operation, we obtained side product **8**, from a 1,2-addition of 3-$ClC_6H_4CO_2H$ to gold α-carbonylcarbenoid **III**. The yields of the desired 2,3-dihydrofurans **2** are highly dependent on the nucleophilicity of the alkene partner, although were satisfactory in most instances. This synthesis used external promoter, *m*-CPBA as a source of oxygen, to generate α-carbonylcarbenoid **III**.

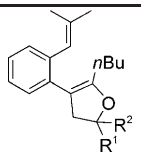
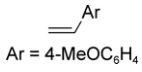
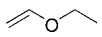
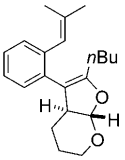
## Conclusion

Previously, reactions of gold α-carbonylcarbenoids generated from redox reactions were restricted to intramolecular cyclizations.[2–4] We have reported the feasibility for catalytic [3+2] cycloadditions of gold α-carbonylcarbenoids with alkenes, to give 2,3-dihydrofuran products efficiently. The generation of such carbenoids relies on an intramolecular redox reaction of alkyne–epoxide functionalities, which avoids the use of diazocarbonyl precursors. Unlike reported rhodium and copper catalysis, this cycloaddition is compatible with a diverse assortment of alkenes, which include α-substituted styrenes, enol ethers, and 2,3-dimethylbutadienes. Deuterium-labeling experiments indicate a stepwise ionic mechanism for the [3+2] cycloaddition pathway. This pathway suggests that [3+2] cycloaddition is difficult to achieve with high enantioselectivity. The value of this gold catalysis is demonstrated by the stereocontrolled formation of various oxacyclic products through the HOTf treatment of 2,3-dihydrofurans. In the ene–oxonium cyclization, we obtained distinct products **3** and **3′**, presumably produced from a stepwise and concerted mechanisms respectively. Further appli-

Table 8. One-pot transformation of enyne **I-1a** into 2,3-dihydrofurans.




| Entry | Alkene[a] | Conditions | Products [%][b] | **8** [%] |
|---|---|---|---|---|
| | | |  | |
| 1 |  Ar = 4-MeOC$_6$H$_4$ | [AuCl(PPh$_3$)] (5%) AgSbF$_6$ (2%), 12 h | **2a**, R$^1$ = H, R$^2$ = 4-MeOC$_6$H$_4$ (46) | 41 |
| 2 |  | [AuCl(PPh$_3$)] (5%) AgSbF$_6$ (2%), 12 h | **2c**, R$^1$ = Me, R$^2$ = Ph (61) | 27 |
| 3 |  | [AuCl(PPh$_3$)] (5%) AgSbF$_6$ (2%), 6 h | **2f**, R$^1$ = R$^2$ = Ph (66) | 14 |
| 4 |  | [AuCl{P(*t*Bu)$_2$(*o*-biphenyl)}] (5%) AgNTf$_2$ (2%), 3 h | **2g**, R$^1$ = H, R$^2$ = OEt (72) | 21 |
| 5 |  | [AuCl{P(*t*Bu)$_2$(*o*-biphenyl)}] (5%) AgNTf$_2$ (2%), 3 h | **4d** (59%)  | 27 |

[a] [**I-1a**] = 0.08 M, alkene (10 equiv). [b] Yields are reported after separation on a silica column.

cation of this new catalysis to bioactive molecules is under current investigation.

## Experimental Section

**General**: Unless otherwise noted, all reactions were carried out under a nitrogen atmosphere in oven-dried glassware using a standard syringe, cannula, and septa apparatus. Benzene, diethyl ether, tetrahydrofuran, and hexane were dried with sodium benzophenone and distilled before use. Dichloromethane was dried over $CaH_2$ and distilled before use. NMR spectra were run at 400 ($^1$H) or 100 MHz ($^{13}$C) in $CDCl_3$.

**Typical procedure for the synthesis of 1a**: *n*BuLi (2.4 mL, 2.5 M, 5.9 mmol) was added to a solution of isopropyltriphenylphosphonium iodide (2.76 g, 6.4 mmol) in THF (25 mL) at 0 °C and the mixture was stirred at 0 °C for 1 h. 2-(Hex-1-ynyl)benzaldehyde (0.99 g, 4.9 mmol) was added and the mixture was stirred at 23 °C for 4 h. The solution was quenched with water and concentrated in vacuo. The organic layer was extracted with diethyl ether, dried over $MgSO_4$, and concentrated in vacuo. The residue was eluted through a silica column (hexane) to give the olefination product as a colorless oil (0.91 g, 4.3 mmol, 88%). *m*-CPBA (1.12 g, 6.5 mmol) was added to the enyne compound (0.91 g, 4.3 mmol) in dichloromethane (30 mL) and the mixture was stirred for 8 h at 0 °C. The resulting solution was quenched with an aqueous solution of $NaHCO_3$, extracted with diethyl ether, dried over anhydrous $MgSO_4$, and concentrated in vacuo. The resulting mass was filtered through a small basic $Al_2O_3$ bed, then concentrated in vacuo, and eluted through a $Et_3N$-pretreated silica column (EtOAc/hexane 1:9) to afford **1a** as a colorless oil (0.77 g, 3.4 mmol, 79%).

**Compound 2a**: A solution of $PPh_3AuSbF_6$ (2 mol%) was prepared by mixing [AuCl(PPh$_3$)] (10.0 mg, 0.02 mmol) and $AgSbF_6$ (3.1 mg, 0.009 mmol) in dichloromethane (1.0 mL) for 10 min. Compound **1a** (100 mg, 0.44 mmol) and 4-vinyl-1-methoxybenzene (295 mg, 2.2 mmol) in dichloromethane (3.4 mL) were added dropwise to the resulting mixture at 23 °C and the solution was stirred for 6 h at 40 °C. The solution was filtered through a Celite bed, then concentrated in vacuo, and eluted through a silica-gel column (EtOAc/hexane 1:9) to give compound **2a** as a colorless oil (102 mg, 0.28 mmol, 64%).

**Compound 3a**: A 1% solution of trifluoromethanesulfonic acid in dichloromethane (1.0 mL) was added to a solution of compound **2a** (102 mg, 0.28 mmol) in dichloromethane (38 mL) and the mixture was stirred at 23 °C for 3 h. The solution was quenched with water, the organic layer was extracted with dichloromethane, dried over $MgSO_4$, and concentrated in vacuo. The residue was eluted through a silica column (EtOAc/hexane 1:10) to give **3a** as a colorless oil (54.0 mg, 0.15 mmol, 54%).

**One-pot synthesis of 2,3-dihydrofurans**: 1-(Hex-1-ynyl)-2-(2-methylprop-1-enyl)benzene (120 mg, 0.57 mmol) in dichloromethane (2.0 mL) was added to a solution of *m*-CPBA (117 mg, 0.68 mmol) and $NaHCO_3$ (56 mg, 0.68 mmol) in dichloromethane (3.0 mL) to give solution A and the mixture was stirred at room temperature. The epoxide formation was monitored by TLC. After completion of the epoxide, a solution of $PPh_3AuSbF_6$ (2 mol%) was prepared by mixing [AuCl(PPh$_3$)] (13.8 mg, 0.03 mmol) and $AgSbF_6$ (4.4 mg, 0.01 mmol) in dichloromethane (2.0 mL) for 10 min. The appropriate styrene (10 equiv) was then added to give solution B. Solution B was added to solution A and the mixtures were stirred for 3–12 h at 40 °C. The resulting solution was filtered through a Celite bed, concentrated in vacuo, and eluted through a silica-gel column to give the product.

Spectral data of compounds **1a**, **I-1a**, **2a**, **3a**, and **3a′** are listed below. Other spectral data and copies of the $^1$H and $^{13}$C NMR spectra of all compounds are given in the Supporting Information.

**Compound 1a**: $^1$H NMR (400 MHz, $CDCl_3$): $\delta$ = 7.35 (d, $J$ = 7.6 Hz, 1H), 7.25–7.22 (m, 2H), 7.20–7.16 (m, 1H), 4.04 (s, 1H), 2.44 (t, $J$ = 7.2 Hz, 2H), 1.67–1.54 (m, 2H), 1.52–1.43 (m, 5H), 1.01 (s, 3H), 0.93 ppm (t, $J$ = 7.6 Hz, 3H); $^{13}$C NMR (100 MHz, $CDCl_3$): $\delta$ = 138.7, 131.4, 127.3, 126.9, 126.0, 122.3, 95.2, 78.1, 64.2, 61.1, 30.9, 24.6, 22.0, 19.2, 18.2, 13.6 ppm; IR (neat): $\tilde{\nu}$ = 3085 (m), 2958 (s), 2155 (w), 1605 (m), 1458 cm$^{-1}$ (s); HRMS: $m/z$: calcd for $C_{16}H_{20}O$: 228.1514; found: 228.1511.

**Compound I-1a**: $^1$H NMR (400 MHz, $CDCl_3$): $\delta$ = 7.41 (d, $J$ = 7.6 Hz, 1H), 7.27–7.21 (m, 2H), 7.15–7.11 (m, 1H), 6.51 (s, 1H), 2.47 (t, $J$ = 6.8 Hz, 2H), 1.96 (s, 3H), 1.84 (s, 3H), 1.65–1.51 (m, 4H), 0.98 ppm (t, $J$ = 7.2 Hz, 3H); $^{13}$C NMR (100 MHz, $CDCl_3$): $\delta$ = 140.3, 135.9, 132.0, 128.9, 126.9, 125.7, 124.2, 123.4, 94.5, 79.7, 30.9, 26.6, 21.9, 19.5, 19.2, 13.6 ppm; IR (neat): $\tilde{\nu}$ = 3150 (s), 2958 (s), 2200 (w), 1657 (m), 1473 cm$^{-1}$ (s); HRMS: $m/z$: calcd for $C_{16}H_{20}$: 212.1565; found: 212.1564.

**Compound 2a**: $^1$H NMR (400 MHz, $CDCl_3$): $\delta$ = 7.33 (d, $J$ = 8.8 Hz, 2H), 7.18–7.15 (m, 4H), 6.90 (d, $J$ = 8.4 Hz, 2H), 6.13 (s, 1H), 5.47 (dd, $J$ = 10.4, 8.0 Hz, 1H), 3.8 (s, 3H), 3.25 (dd, $J$ = 14.8, 10.4 Hz, 1H), 2.89 (dd, $J$ = 14.4, 7.6 Hz, 1H), 2.07 (t, $J$ = 7.2 Hz, 2H), 1.82 (s, 3H), 1.72 (s, 3H), 1.52–1.45 (m, 2H), 1.30–1.23 (m, 2H), 0.82 ppm (t, $J$ = 7.2 Hz, 3H); $^{13}$C NMR (100 MHz, $CDCl_3$): $\delta$ = 159.1, 153.5, 137.6, 135.8, 135.3, 134.2, 129.8, 129.6, 127.1 (2×CH), 126.0 (2× CH), 125.1, 113.9 (2×CH), 107.5, 80.7, 55.3, 43.6, 29.0, 26.5, 26.2, 22.6, 19.2, 13.8 ppm; IR (neat): $\tilde{\nu}$ = 3087

(m), 2945 (s), 1615 (s), 1604 (m), 1217 (m), 1118 $cm^{-1}$ (s); HRMS: *m/z*: calcd for $C_{25}H_{30}O_2$: 362.2246; found: 362.2245.

**Compound 3a**: $^1H$ NMR (400 MHz, $CDCl_3$): $\delta = 7.52$ (d, $J = 7.6$ Hz, 1H), 7.27–7.17 (m, 5H), 6.84 (d, $J = 8.8$ Hz, 2H), 4.62 (t, $J = 6.8$ Hz, 1H), 3.77 (s, 3H), 3.50–3.47 (m, 1H), 2.16 (t, $J = 10.0$ Hz, 2H), 2.11 (s, 6H), 1.96 (t, $J = 8.0$ Hz, 2H), 1.34–1.24 (m, 4H), 0.85 ppm (t, $J = 6.8$ Hz, 3H); $^{13}C$ NMR (100 MHz, $CDCl_3$): $\delta = 158.9$, 146.2, 142.4, 137.6, 134.2, 131.9, 127.4 (2×CH), 126.8, 126.7, 125.0, 124.4, 113.7 (2×CH), 94.6, 78.3, 55.3, 52.2, 44.1, 38.0, 26.4, 23.5, 23.2, 22.9, 14.1 ppm; IR (neat): $\tilde{\nu} = 3100$ (m), 2951 (s), 1605 (s), 1150 $cm^{-1}$ (s); HRMS: *m/z*: calcd for $C_{25}H_{30}O_2$: 362.2246; found: 362.2243.

**Compound 3a′**: $^1H$ NMR (400 MHz, $CDCl_3$): $\delta = 7.27$–$7.19$ (m, 5H), 7.11–7.09 (m, 1H), 6.82 (d, $J = 8.8$ Hz, 2H), 5.02 (s, 1H), 4.83 (m, 1H), 4.46 (dd, $J = 11.2$, 3.6 Hz, 1H), 3.87 (s, 1H), 3.77 (s, 3H), 3.73 (d, $J = 7.6$ Hz, 1H), 2.17–2.09 (m, 1H), 2.04–1.97 (m, 1H), 1.87–1.84 (m, 4H), 1.61–1.57 (m, 1H), 1.44–1.37 (m, 4H), 0.96 ppm (t, $J = 6.4$ Hz, 3H); IR (neat): $\tilde{\nu} = 3106$ (m), 2954 (s), 1607 (s), 1153 $cm^{-1}$ (s); HRMS: *m/z*: calcd for $C_{25}H_{30}O_2$: 362.2246; found: 362.2245.

## Acknowledgements

The authors wish to thank the National Science Council, Taiwan for the support of this work.

[1] a) A. Fürstner, P. W. Davies, *Angew. Chem.* **2007**, *119*, 3478–3519; *Angew. Chem. Int. Ed.* **2007**, *46*, 3410–3449; b) E. Jiménez-Núñez, A. M. Echavarren, *Chem. Commun.* **2007**, 333–346; c) D. J. Gorin, F. D. Toste, *Nature* **2007**, *446*, 395–403; d) A. S. K. Hashmi, *Chem. Rev.* **2007**, *107*, 3180–3211; e) A. S. K. Hashmi, G. J. Hutchings, *Angew. Chem.* **2006**, *118*, 8064–8105; *Angew. Chem. Int. Ed.* **2006**, *45*, 7896–7936; f) A. Arcadi, *Chem. Rev.* **2008**, *108*, 3266–3325; g) E. Jiménez-Núñez, A. M. Echavarren, *Chem. Rev.* **2008**, *108*, 3326–3350.

[2] α-Carbonyl gold carbenoids from $Ph_2SO$-induced redox reactions, see: a) N. D. Shapiro, F. D. Toste, *J. Am. Chem. Soc.* **2007**, *129*, 4160–4161; b) C. A. Witham, P. Mauleón, N. D. Shapiro, B. D. Sherry, F. D. Toste, *J. Am. Chem. Soc.* **2007**, *129*, 5838–5839; c) G. Li, L. Zhang, *Angew. Chem.* **2007**, *119*, 5248–5251; *Angew. Chem. Int. Ed.* **2007**, *46*, 5156–5159; d) P. W. Davies, S. J.-C. Albrecht, *Chem. Commun.* **2008**, 238–240; e) A. B. Cuenca, S. Montserrat, K. M. Hossain, G. Mancha, A. Lledós, M. Medio-Simón, G. Ujaque, G. Asensio, *Org. Lett.* **2009**, *11*, 4906–4909.

[3] a) L. Cui, G. Zhang, Y. Peng, L. Zhang, *Org. Lett.* **2009**, *11*, 1225–1228; b) L. Cui, Y. Peng, L. Zhang, *J. Am. Chem. Soc.* **2009**, *131*, 8394–8395; c) H.-S. Yeom, J.-E. Lee, S. Shin, *Angew. Chem.* **2008**, *120*, 7148–7151; *Angew. Chem. Int. Ed.* **2008**, *47*, 7040–7043.

[4] Although $AgSbF_6$ alone enabled the cycloisomerization of epoxyalkynes to carbocyclic products, we were not able to trap the corresponding α-carbonylcarbenoids with $Ph_2SO$ or styrene; see reference [5a]; a) G.-Y. Lin, C.-W. Li, S.-H. Hung, R.-S. Liu, *Org. Lett.* **2008**, *10*, 5059–5062; b) A. S. K. Hashmi, M. Bührle, R. Salathé, J. W. Bats, *Adv. Synth. Catal.* **2008**, *350*, 2059–2064.

[5] Gold-catalyzed rearrangement of propargyl acetates provides reactive intermediates that are synthetic equivalents of gold α-carbonyl carbenoids; see selected examples: a) X. Shi, D. J. Gorin, F. D. Toste, *J. Am. Chem. Soc.* **2005**, *127*, 5802–5803; b) Y. Harrak, C. Blaszykowski, M. Bernard, K. Cariou, E. Mainetti, V. Mouries, A.-L. Dhimane, L. Fensterbank, M. Malacria, *J. Am. Chem. Soc.* **2004**, *126*, 8656–8657; c) V. Mamane, T. Gress, H. Krause, A. Fürstner, *J. Am. Chem. Soc.* **2004**, *126*, 8654–8655; d) A. Fürstner, P. Hannen, *Chem. Eur. J.* **2006**, *12*, 3006–3019; e) A. Fürstner, A. Schlecker, *Chem. Eur. J.* **2008**, *14*, 9181–9191; f) E. Jiménez-Núñez, M. Raducan, T. Lauterbach, K. Molawi, C. R. Solorio, A. M. Echavarren, *Angew. Chem.* **2009**, *121*, 6268–6271; *Angew. Chem. Int. Ed.* **2009**, *48*, 6152–6155; g) A. S. K. Hashmi, M. Rudolph, H.-U. Siehl, M. Tanaka, J. W. Bats, W. Frey, *Chem. Eur. J.* **2008**, *14*, 3703–3708.

[6] For the debate of the role of gold-carbenoid or gold-stabilized allyl cation for gold alkenylcarbenoid species, see: a) D. Benitez, N. D. Shapiro, E. Tkatchouk, Y. Wang, W. A. Goddard, F. D. Toste, *Nat. Chem. Biol.* **2009**, *1*, 482–486; b) G. Seidel, R. Mynott, A. Fürstner, *Angew. Chem.* **2009**, *121*, 2548–2551; *Angew. Chem. Int. Ed.* **2009**, *48*, 2510–2513; c) A. Fürstner, L. Morency, *Angew. Chem.* **2008**, *120*, 5108–5111; *Angew. Chem. Int. Ed.* **2008**, *47*, 5030–5033; d) A. S. K. Hashmi, *Angew. Chem.* **2008**, *120*, 6856–6858; *Angew. Chem. Int. Ed.* **2008**, *47*, 6754–6756.

[7] a) G. Lemière, V. Gandon, K. Cariou, A. Hours, T. Fukuyama, A.-L. Dhimane, L. Fensterbank, M. Malacria, *J. Am. Chem. Soc.* **2009**, *131*, 2993–3006; b) J. H. Lee, F. D. Toste, *Angew. Chem.* **2007**, *119*, 930–932; *Angew. Chem. Int. Ed.* **2007**, *46*, 912–914; c) S. Bhunia, R.-S. Liu, *J. Am. Chem. Soc.* **2008**, *130*, 16488–16489.

[8] The [3+2] cycloaddition refers to aldehydes rather than alkenes, see: a) N. D. Shapiro, F. D. Toste, *J. Am. Chem. Soc.* **2008**, *130*, 9244–9245; b) N. D. Shapiro, Y. Shi, F. D. Toste, *J. Am. Chem. Soc.* **2009**, *131*, 11654–11655; c) G. Zhang, L. Zhang, *J. Am. Chem. Soc.* **2008**, *130*, 12598–12599.

[9] a) M. E. Alonso, A. Morales, A. W. Chitty, *J. Org. Chem.* **1982**, *47*, 3747–3754; b) M. C. Pirrung, J. Zhang, K. Lackey, D. D. Sternbach, F. Brown, *J. Org. Chem.* **1995**, *60*, 2112–2124; c) E. Wenkert, M. E. Alonso, B. L. Buckwalter, K. J. Chou, *J. Am. Chem. Soc.* **1977**, *99*, 4778–4782; d) E. Wenkert, M. E. Alonso, B. L. Buckwalter, E. L. Sanchez, *J. Am. Chem. Soc.* **1983**, *105*, 2021–2029; e) M. E. Alonso, P. Jano, M. I. Hernandez, *J. Org. Chem.* **1983**, *48*, 3047–3050; f) E. J. Park, S. H. Kim, S. Chang, *J. Am. Chem. Soc.* **2008**, *130*, 17268–17269.

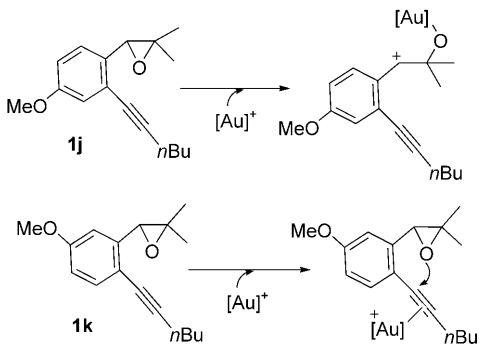
[10] a) M. J. Johansson, D. J. Gorin, S. T. Staben, F. D. Toste, *J. Am. Chem. Soc.* **2005**, *127*, 18002–18003; b) S. López, E. Herrero-Gómez, P. Pérez-Galán, C. Nieto-Oberhuber, A. M. Echavarren, *Angew. Chem.* **2006**, *118*, 6175–6178; *Angew. Chem. Int. Ed.* **2006**, *45*, 6029–6032.

[11] For rhodium-catalyzed [3+2] cycloaddition of alkenylcarbenoids with enol ethers; see a) H. M. L. Davies, B. Xiang, N. Kong, D. G. Stafford, *J. Am. Chem. Soc.* **2001**, *123*, 7461–7462; b) H. M. L. Davies, B. Hu, E. Saikali, P. R. Bruzinski, *J. Org. Chem.* **1994**, *59*, 4535–4541.

[12] a) C. Nieto-Oberhuber, M. P. Muñoz, E. Buñuel, C. Nevado, D. J. Cárdenas, A. M. Echavarren, *Angew. Chem.* **2004**, *116*, 2456–2460; *Angew. Chem. Int. Ed.* **2004**, *43*, 2402–2406; b) C. Nieto-Oberhuber, S. López, A. M. Echavarren, *J. Am. Chem. Soc.* **2005**, *127*, 6178–6179; c) S. Díez-González, N. Marion, S. P. Nolan, *Chem. Rev.* **2009**, *109*, 3612–3676; d) F. Gagosz, *Org. Lett.* **2005**, *7*, 4129–4132.

[13] Results of catalyst screening of epoxides **1a** with enol ether are provided in the Supporting Information.

[14] We did not obtain the desired 2,3-dihydrofurans from epoxides **1j** and **1k**. Epoxide **1j** favors ring-opening to induce epoxy–ketone rearrangement. For species **1k**, the epoxide is expected to attack at the alkynyl-C(2) carbon to alter reaction pathway. We obtained a messy mixture of products with the two epoxides. Spectral data of epoxides **1j** and **1k** are provided in the Supporting Information.



[15] NOE spectra of key compounds are provided in the Supporting Information; CCDC-759967 (**3l**) contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

[16] Preparation of *cis*-deuterated styrene is described in the Supporting Information; see: G. Vassilikogiannakis, M. Hatzimarinaki, M. Orfanopoulos, *J. Org. Chem.* **2000**, *65*, 8180–8187.

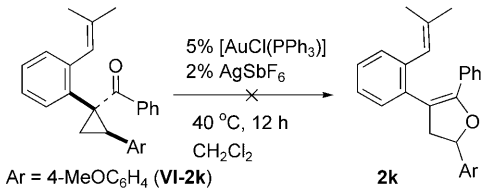
[17] Preparation of *trans*-deuterated styrene, see: a) H.-W. You, K.-J. Lee, *Synlett* **2001**, 105–107; b) K. P. Gable, F. A. Zhuravlev, *J. Am. Chem. Soc.* **2002**, *124*, 3970–3979.

[18] Cyclopropyl ketones with a β-substituted silylmethyl or 1-siloxyvinyl group were required for the operation at mild temperatures, see a) V. K. Yadav, R. Balamurugan, *Org. Lett.* **2001**, *3*, 2717–2719; b) H. M. L. Davies, G. Ahmed, R. L. Calvo, M. R. Churchill, D. G. Churchill, *J. Org. Chem.* **1998**, *63*, 2641–2645.

[19] We obtained **2k** and cyclopropanation product **VI-2k** in 68 and 14% yields, respectively, in the gold catalysis (Table 2, entry 3). Treatment of this cyclopropyl ketone with the same [AuCl($PPh_3$)]/$AgSbF_6$ catalyst under the same conditions failed to give **2k** in a tractable amount. Spectral data of the cyclopropylketone is provided in the Supporting Information.

[20] A concerted pathway was established for an intramolecular ene–oxonium reaction, see reference [20a]. For reviews for ene reactions, see: a) K. Mikami, M. Shimizu, *Chem. Rev.* **1992**, *92*, 1021; b) B. B. Snider, *Acc. Chem. Res.* **1980**, *13*, 426–432.

[21] For intramolecular ene–oxonium reactions, see: a) T. A. Blumenkopf, G. C. Look, L. E. Overman, *J. Am. Chem. Soc.* **1990**, *112*, 4399–4403; b) L. E. Overman, A. S. Thompson, *J. Am. Chem. Soc.* **1988**, *110*, 2248–2256; c) T. A. Blumenkopf, M. Bratz, A. Castañeda, G. C. Look, L. E. Overman, D. Rodriguez, A. S. Thompson, *J. Am. Chem. Soc.* **1990**, *112*, 4386–4399; d) H. Ohmura, G. D. Smyth, K. Mikami, *J. Org. Chem.* **1999**, *64*, 6056–6059.




Received: January 4, 2010
Revised: February 23, 2010
Published online: April 8, 2010