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Divergent Synthetic Routes for Ring Expansion or Cyclization from 1,4-Allylic Diol Derivatives via Gold(I) Catalysis or Zinc(II) Mediation

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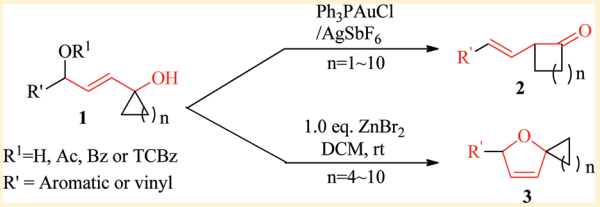
Supporting Information

ABSTRACT: A new efficient method was developed to transform cyclic alkanols into one-carbon higher homologated ketones using various esters as the leaving groups through gold-catalyzed allylic cation-promoted pinacol-type rearrangement. This reaction, coupled with oxy-Cope rearrangement, provided a new strategy to synthesize five-carbon homologated ring ketones. In addition, using $ZnBr_2$, 2,5-dihydrofuran products were obtained in moderate to good yields via an intramolecular cyclization process.



INTRODUCTION

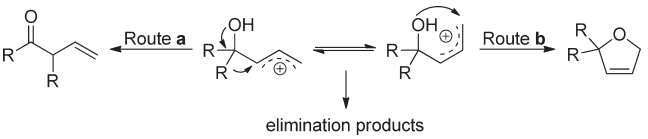
Ring expansion or carbon chain extension by means of carbon-insertion procedures have been employed frequently in organic synthesis.[1] In this field, the carbon cation-induced pinacol-type rearrangement is of particular importance, with its utility being demonstrated in a variety of synthetic applications.[2] However, a similar transformation, the allylic cation-promoted pinacol-type rearrangement, as exemplified by the reaction (route **a**) shown in Scheme 1, has received much less attention. This may be because of the improved stability and low isomerization activity of this vinyl conjugated carbon cation system and the possible competitive formation of the 2,5-dihydrofurans (route **b**) and the elimination products.[3,4]

Methods for ring expansion of the small ring molecules using transition metal catalysts have been well developed. For example, Toste's group reported the intramolecular ring expansion of alkynyl cyclopropanols/cyclobutanols via gold catalysis[5] and then extended this to an asymmetric version by using allenyl cyclopropanols as substrates.[6,7] Yu developed a cation-triggered ring expansion process, in which alkynyl cyclopropanes were transformed into alkylidene cyclobutylamines using gold catalysts.[8] Nevertheless, from the same substrates, Liu's group found that cyclobutenyl ketones can be obtained through an oxidative ring-expansion pathway, which was triggered by gold-catalyzed nucleophilic addition of oxygen-delivering oxidants, such as diphenylsulfoxide, onto alkynes.[9] Besides these gold-catalyzed reactions,[10] other transition metal catalysts, such as Fe,[11] Ru,[12] Rh,[13] Co,[14] Pd,[15] and Pt[16] complexes, have also been utilized successfully in numerous ring-expansion reactions. However, all of these studies focused on the small ring structures, primarily on cyclopropane derivatives.

On the basis of our previous studies of the gold-catalyzed reaction of allylic esters,[17] we presumed that the allylic cation intermediate, generated from allylic esters via gold catalysis, might promote the cyclic alkanol's ring expansion. As a continuation of our previous research, we herein report a new ring-expansion pathway to synthesize one-carbon higher homologated ring ketones from cycloalkanols through gold-catalyzed allylic cation-promoted pinacol-type rearrangement, in which the medium- and large-sized ring substrates worked very well.

Additionally, we also prepared a series of 2,5-dihydrofurans from the same substrates using $ZnBr_2$ as the reaction mediator. 2,5-Dihydrofurans and their derivatives are structural motifs that are found frequently in a wide variety of natural products[18,19] and therefore have aroused great interest for the development of new synthetic methods.

Scheme 1. Divergent Reaction Routes



RESULTS AND DISCUSSION

Considering that six-membered rings are the most stable cyclic structure, we chose the cyclohexanol derivative **A** (entry 1, Table 1) as the model system for our initial investigation. When compound **A** was treated with $AuCl_3$ in DCE at rt, cycloheptanone **2a** was obtained in 11% yield, along with a mixture of β-elimination products,[20] without formation of dihydrofuran **3a**. Using $AuPPh_3Cl$/$AgSbF_6$ as catalyst, **2a** was obtained in 21% yield (entry 2,

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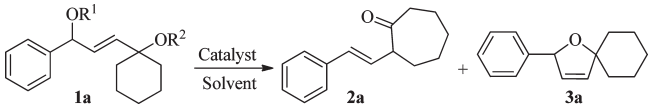
Table 1. Optimization of the Reaction of 1a To Give Ring-Expansion Product 2a or Cyclization Product 3a[a]



	(R^1/R^2)	catalyst (%)	solvent/temp (°C)	yield (%) (**2a**/**3a**)
1	H/H (**A**)	$AuCl_3$ (10)	DCE/rt	11/0
2	H/H (**A**)	$AuPPh_3Cl/AgSbF_6$ (10)	DCM/30	21/0
3	H/THP (**B**)	$AuCl_3$ (10)	DCE/rt	18/0
4	Ac/H (**C**)	$AuCl_3$ (10)	DCE/rt	28/0
5	Ac/THP (**D**)	$AuCl_3$ (10)	DCE/rt	13/0
6	Bz/H (**E**)	$AuCl_3$ (10)	DCE/rt	0/0
7	Bz/H (**E**)	$AuPPh_3Cl/AgSbF_6$ (10)	DCE/rt	47/0
8	Bz/H (**E**)	$AuPPh_3Cl/AgSbF_6$ (10)	DCM/30	71/0
9	Piv/H (**F**)	$AuPPh_3Cl/AgSbF_6$ (10)	DCM/30	63/0
10	TCBz/H (**1a**)	$AuPPh_3Cl/AgSbF_6$ (10)	DCM/30	84/0
11	TCBz/H (**1a**)	$AuPPh_3Cl$ (10)	DCM/30	0/0
12	TCBz/H (**1a**)	$AgSbF_6$ (10)	DCM/30	43/0
13	TCBz/H (**1a**)	$AuPPh_3Cl/AgSbF_6$ (5)	DCM/30	81/0
14	TCBz/H (**1a**)	$AuPPh_3Cl/AgSbF_6$ (2)	DCM/30	59/0
15	TCBz/H (**1a**)	$ZnBr_2$[b]	DCM/rt	Trace/80
16	TCBz/H (**1a**)	HCl (10)	DCM/30	0/0
17	TCBz/H (**1a**)	CF_3SO_3H (10)	DCM/30	22/18
18	TCBz/H (**1a**)	$BF_3 \cdot Et_2O$ (10)	DCM/30	26/0
19	TCBz/H (**1a**)	$Cu(OTf)_2$ (5)	DCM/30	48/14

[a] Unless noted, all reactions were carried out at 0.1 mmol scale in 4 mL of solvent for 4 h. [b] 1 mol % of $ZnBr_2$ was used at rt. Ac = acetate, Bz = benzoate, Piv = pivalate, TCBz = 2,4,6-trichlorobenzoate.

Table 1). Replacement of the hydroxyl group by THP ether (R^2 position, compound **B**, entry 3, Table 1) and acetate (R^1 position, compound **C**, entry 4, Table 1) either separately or simultaneously (compound **D**, entry 5, Table 1) did not improve the yield of **2a**. Investigation of benzoate substrate **E** afforded no desired product using $AuCl_3$, but when $AuPPh_3Cl/AgSbF_6$ (10 mol %) was used as catalyst, **2a** was obtained in 47% yield (entries 6 and 7, Table 1). Solvent and reaction temperature were optimized, which led to a considerable improvement in **2a**'s yield (entry 8, Table 1). Using pivalate as the protecting group to increase the steric bulk (**F**, entry 9, Table 1) was ineffective, so we turned to exploring the electronic effect on the reaction yield. When electron-deficient 2,4,6-trichloro benzoate (TCBz) was used as the protecting group (**1a**, entry 10, Table 1), **2a** was obtained in 84% yield. Employing $AgSbF_6$ alone led to a lower yield, and Ph_3PAuCl alone was totally inactive (Table 1, entries 11 and 12). When 5 mol % catalyst was used, **2a**'s yield was slightly reduced (Table 1, entry 13). A variety of other Lewis and Brønsted acids were also tested.[21] When 1 mol % of $ZnBr_2$ was used as catalyst, 2,5-dihydrofuran **3a** was obtained in 80% yield (Table 1, entry 15). In control experiments, Brønsted acids HCl and CF_3SO_3H afforded no product, whereas $BF_3 \cdot Et_2O$ gave **2a** in 26% yield (Table 1, entries 16−18).

Kirsch's group has developed a similar ring-expansion pathway using $Cu(OTf)_2$ as catalyst,[4] but this method did not work for six-membered rings. As a comparison, we investigated cyclohexane substrate **1a**'s reaction using 5 mol % $Cu(OTf)_2$ catalyst, which interestingly provided **2a** in 48% yield and **3a** in 14% yield (Table 1, entry 19). This meant that the presence of the OTCBz group played a pivotal role in this transformation. However, the use of different metal complexes (such as Cu or Au) also affected the reaction outcomes.

Using the conditions from entry 13 in Table 1, the scope and limitations of the ring expansion reaction were explored. A number of cyclic and linear substrates with different protection patterns were tested, which provided the corresponding higher homologated cyclic and linear ketones. As shown in Table 2, in the reaction of three- and four-membered rings, unprotected 2-butene-1,4-diols **1b** and **1c** were used, which provided cyclic butanone **2b** and pentanone **2c** in 81% and 72% yield, respectively. For the five-membered substrates, allylic acetate containing cyclopentanols were employed. Both electron-rich and electron-poor reactants worked very well, giving the corresponding cyclohexanones in moderate to good yields (Table 2, entries 3−6). It was notable that the catalyst loading in all of the small rings' reactions was less than 5%.

We then investigated the transformation of cyclohexanol. For electron-deficient arene substrates, TCBz was used as protecting group, which gave the desired products in good yields (Table 2, entries 7−9), but for their electron-rich analogues, the acetyl group was employed instead.[22] This provided the desired products in moderate yields (Table 2, entries 10 and 11). Large-sized ring compounds, such as cycloheptanol, cyclooctanol, and cyclododecanol, were also tested. They exhibited higher reactivities, giving the homologated cyclic ketones in good yields (Table 2, entries 12−14). However, although 10 mol % of catalyst was used, the reaction of styryl substrate **1p** gave **2p** in a low yield (Table 2, entry 15). Furthermore, the alkyl substrate

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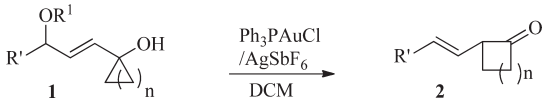
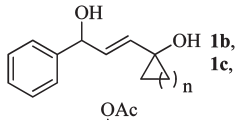
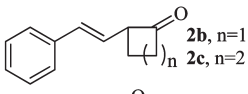
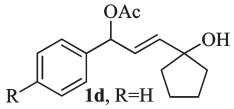
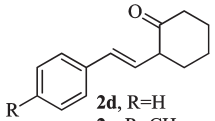
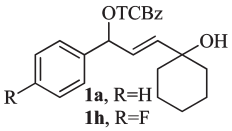
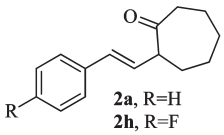
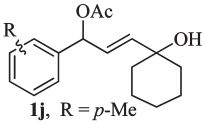
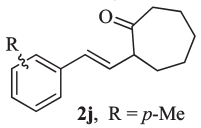
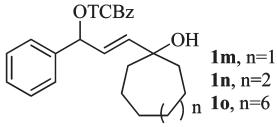
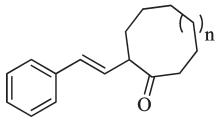
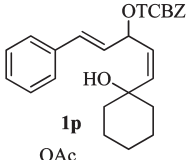
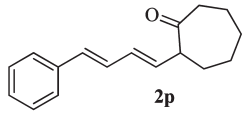
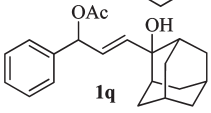
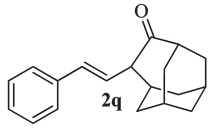
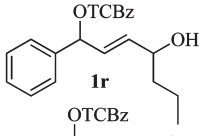
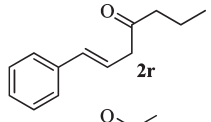
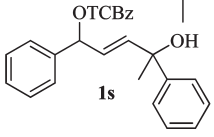
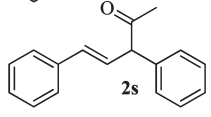
Table 2. Preparation of One-Carbon Higher Homologated Cyclic Ketones through Gold-Catalyzed Ring Expansion[a]



Entry	Substrate	%Cat.	Time [h] / Temp.[oC]	Product	Yield
1	 **1b**, n=1	2	0.5 / rt	 **2b**, n=1	81%
2	**1c**, n=2	2	0.5 / rt	**2c**, n=2	72%
3	 **1d**, R=H	3	1 / rt	 **2d**, R=H	83%
4	**1e**, R=CH_3	3	2 / rt	**2e**, R=CH_3	91%
5	**1f**, R=MeO	3	3 / rt	**2f**, R=MeO	84%
6	**1g**, R=F	3	3 / rt	**2g**, R=F	74%
7	 **1a**, R=H	5	1 / 30	 **2a**, R=H	81%
8	**1h**, R=F	5	1 / 30	**2h**, R=F	77%
9	**1i**, R=Br	5	1 / 30	**2i**, R=Br	74%
10	 **1j**, R = *p*-Me	5	2 / 30	 **2j**, R = *p*-Me	51%
11	**1k**, R = *o*-Me	5	2 / 30	**2k**, R = *o*-Me	50%
12	 **1m**, n=1	5	0.5 / 30	 **2m**, n=1	81%
13	**1n**, n=2	5	0.5 / 30	**2n**, n=2	86%
14	**1o**, n=6	5	1 / rt	**2o**, n=6	89%
15	 **1p**	10	2/30	 **2p**	28%
16	 **1q**	10	7/30	 **2q**	34%
17	 **1r**	5	12 / 30	 **2r**	95%
18	 **1s**	5	0.5 / r.t.	 **2s**	95%

[a] Unless noted, all reactions were carried out at 0.1 mmol scale in 4 mL of CH_2Cl_2 at 30 °C.

only afforded a mixture of elimination products, which meant that the presence of a phenyl or vinyl group to stabilize the allylic cation intermediate was vital to this reaction. Transformation of adamantanol **1q** to the homologated cyclic ketone **2q** proceeds smoothly, though with a lower reaction yield (Table 2, entry 16). Two linear substrates were then examined. The reaction of **1r** and **1s** provided ketone **2r** and **2s** in high yields in which the hydrogen atom and the benzene group migrated to the neighboring position (Table 2, entries 17 and 18).

Using the conditions from entry 15 in Table 1, a series of 2,5-dihydrofuran derivatives **3** can be prepared through $ZnBr_2$-induced intramolecular cyclization. Under these conditions, substrate **1h** and **1i** (Table 3, entries 2 and 3), which had an electron-withdrawing phenyl group, worked better than the electron-rich analogues **1j** and **1k**) (Table 3, entries 4 and 5). The bulky adamantanol **1q** can also be transformed into the derivative **3q** in moderate yield. The large-sized rings, such as cycloheptanol **1m**, cyclooctanol **1n** and cyclododecanol **1o**, underwent a similar transformation to give the desired dihydrofurans, together with

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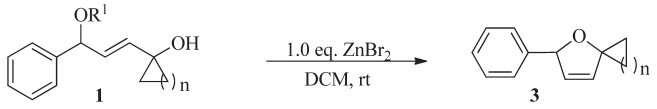
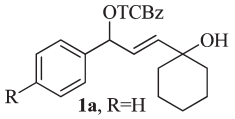
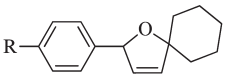
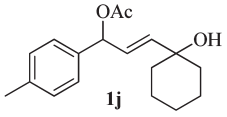
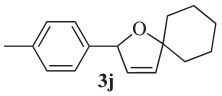
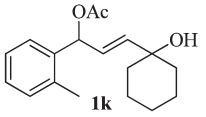
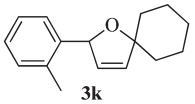
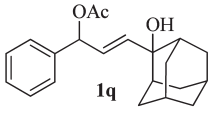
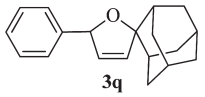
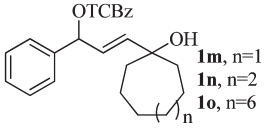
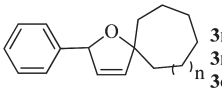
Table 3. Preparation of a Series of 2,5-Dihydrofuran Derivatives through $ZnBr_2$-Mediated Cyclization Reaction[a]



Entry	Substrate	Time(h)	Product	Yield
1	 **1a**, R=H	1	 **3a**, R=H	80%
2	**1h**, R=F	0.5	**3h**, R=F	86%
3	**1i**, R=Br	1.5	**3i**, R=Br	79%
4	 **1j**	0.5	 **3j**	75%
5	 **1k**	0.5	 **3k**	68%
6	 **1q**	0.5	 **3q**	66%
7	 **1m**, n=1	1	 **3m**, n=1	57%(25%)[b]
8	**1n**, n=2	1	**3n**, n=2	37%(31%)[b]
9	**1o**, n=6	1	**3o**, n=6	41%(53%)[b]

[a] Unless noted, all reactions were carried out at 0.1 mmol scale in 4 mL of CH_2Cl_2 at rt. [b] The data in parentheses are the yields of **2m**, **2n**, and **2o**.

the formation of the ring-expansion products. However, small ring substrates (**1b**−**1g**) and linear substrates (**1s**−**1t**) did not work very well using $ZnBr_2$, which primarily provided the ring-enlargement products. Their yields were lower than those of the gold-catalyzed reactions.

To examine the effect of alkene's *Z*/*E* configuration on the reaction yield, compound *Z*-**1a** was prepared and treated with 5 mol % of $Ph_3PAuCl/AgSbF_6$ in DCM. **2a** was obtained in 71% yield, together with 15% yield of **3a**, which is lower than that of **1a** (Scheme 2, eq 1). It seemed that the *Z*-configuration substrate is prone to take cyclization route **b** (Scheme 1). When 1 mol % of $ZnBr_2$ was used as catalyst, only **3a** was obtained in 81% yield (Scheme 2, eq 1).

In the course of **1a**'s reaction, **1a**'s regioisomer **4** can be detected and separated.[23] Treating **4** with 5 mol % of $Ph_3PAuCl/AgSbF_6$ gave **2a** in 90% yield. Furthermore, when $ZnBr_2$ was added, **3a** was obtained in 88% yield (Scheme 2, eq 2). These results indicated that compound **4** is a possible reaction intermediate. Further investigation into compound **4** was performed to elucidate the reaction mechanism.

The different reactivity exhibited by the Au(I) cation and $ZnBr_2$ are intriguing. On the basis of our previous results, the allylic cation intermediates were presumably generated from allylic esters via gold catalysis,[17] to which the neighboring cyclic C−C bonds might serve as intramolecular nucleophiles that react with allylic cations, thereby triggering the pinacol-type rearrangement in a gold-catalyzed transformation. Using $ZnBr_2$, however, the exposed hydroxyl group attacked the allylic cation. Inspired by the previous studies of the tricoordinated gold(I) species,[24] we thought that complexation of the auric cation with the hydroxyl group might prohibit route **b** (Scheme 1). To elucidate the effect of the complexation mode on the reaction outcomes, Lewis acid $BF_3 \cdot Et_2O$, which had only one vacant coordination site available, was then examined. According to the assumption, monocoordinated $BF_3 \cdot Et_2O$ would leave the hydroxyl group exposed, thereby leading to the cyclization products. However, the reaction result did not support this theory; $BF_3 \cdot Et_2O$ gave **2a** as a sole product in 45% yield (Scheme 2, eq 2).

We then explored the possible chirality transfer in these reactions.[25] Chiral substrate (*R*)-**E** was prepared and investigated, which gave **2a** in 0% ee using gold catalysis and provided **3a** in 3% ee in the $ZnBr_2$-mediated reaction (Scheme 3, eq 3). Treating **3a** with the gold catalyst gave no reaction, which indicated that furan **3a** was not the reaction intermediate to afford **4a** (Scheme 3, eq 4).[26] 4-Methyl cyclohexanol substrates with either *syn* (*syn*-**1t**) or *anti* (*anti*-**1t**) configuration were then treated with 5 mol % of $Ph_3PAuCl/AgSbF_6$ in DCM. It was found that *anti*-**1t** mainly provided the *anti*-**2t** (*anti*/*syn* = 12/1), whereas *syn*-**1t** gave a mixture of *anti*-**2t** and *syn*-**2t** (*anti*/*syn* = 1/1.2) (Scheme 3, eq 5).[21]

Although the detailed explanation for the divergent reactivity of the gold and zinc salts was still unclear, a plausible mechanism was proposed. This reaction might have started from the formation of **1a**'s regioisomer **4**,[21] which underwent subsequent ring expansion via gold catalysis or underwent cyclization using $ZnBr_2$. There are two possible transition states in the pinacol

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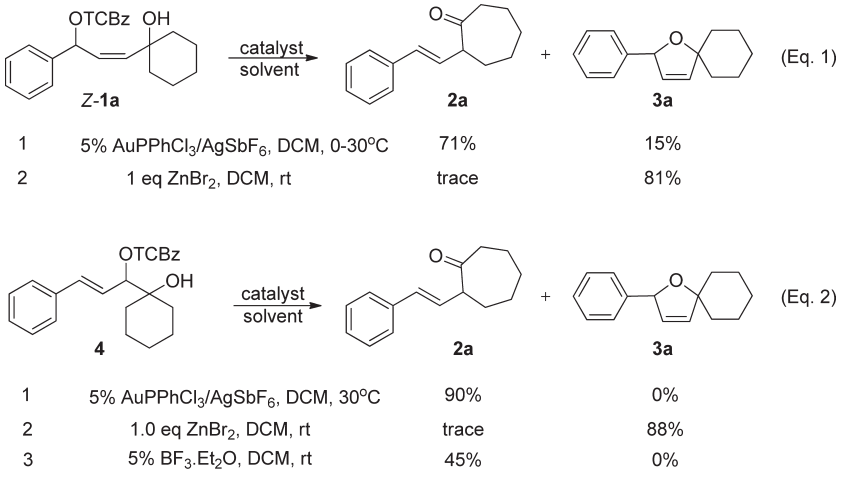
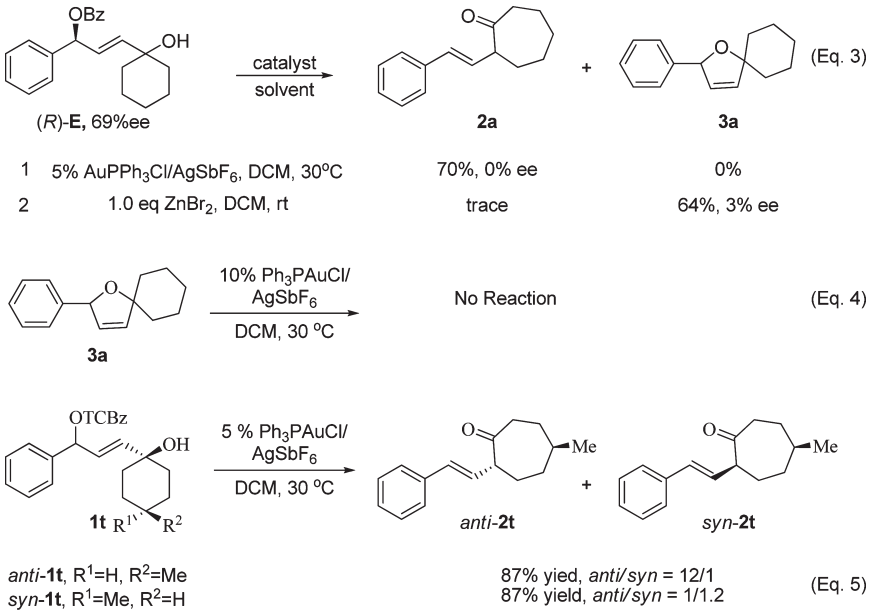
Scheme 2. Examination of the Gold-Catalyzed Reaction of Compound *Z*-1a and 4



Scheme 3. Examination of the Gold-Catalyzed Reaction of Compound (*R*)-E, 3a, and 1t



rearrangement process (Scheme 4), in which an allylic cation intermediate was presumably generated. As compared with transition state **I**, transition state **II** was energetically unfavored, because of the higher 1,3-axial steric hindrance between the hydrogen atom and the bulky allylic ester group. This assumption was further approved by the reactions in eq 5.[21] In the reaction of *anti*-**1t**, the *anti*-methyl group occupied an equatorial position in transition **I** and an axial position in transition **II**, thus making transition **I** more favorable. However, in the reaction of *syn*-**1t**, the *syn*-methyl group occupied an axial position in transition **I** and an equatorial position in transition **II**, which counteracted the allylic cation group and led to a mixture of *anti*-**2t**/*syn*-**2t** with a low ratio. Using $ZnBr_2$, we presumed that an S_N2'-type intramolecular cyclization (transition **III**) might occur to give the 2,5-dihydrogen furan **3a** (Scheme 4). Although no chirality transfer was observed in the reaction of eq 3, which would be implied in a concerted S_N2' transfer, the racemization, however, might occur at the isomerization step. Although compound **4** is thermodynamically more stable than **1a**, the competitive processes, such as pinacol type rearrangement from **4** (route **e**) to give **2a** and direct S_N2 (or S_N1) addition to give **3a** (route **f**), cannot be excluded.

Further derivations for the obtained cyclic ketones were then performed. Ketone **2** can be extended into the higher homologated cyclic ketones. As shown in Scheme 5, addition of ethynyl Grignard to **2a**, followed by hydrogenation and oxy-Cope rearrangement, gave cycloundecanone **7** in high yield.[27] Therefore, a formal five-carbon expansion product was obtained from cyclohexanol **1a** through a pinacol-type rearrangement and then an oxy-Cope rearrangement. Similarly, compound **2p** can be transformed into cycloheptadecanone **8**. Meanwhile, treating **2a** with $NaBH_4$ in MeOH/THF at −20 °C, followed by iodine-induced cyclization, gave bicyclic **10** in 89% yield (*syn*/*anti* = 2.6/1). Compound **2b** can be transformed into butyrolactone **11** using *m*-CPBA as the oxidant.

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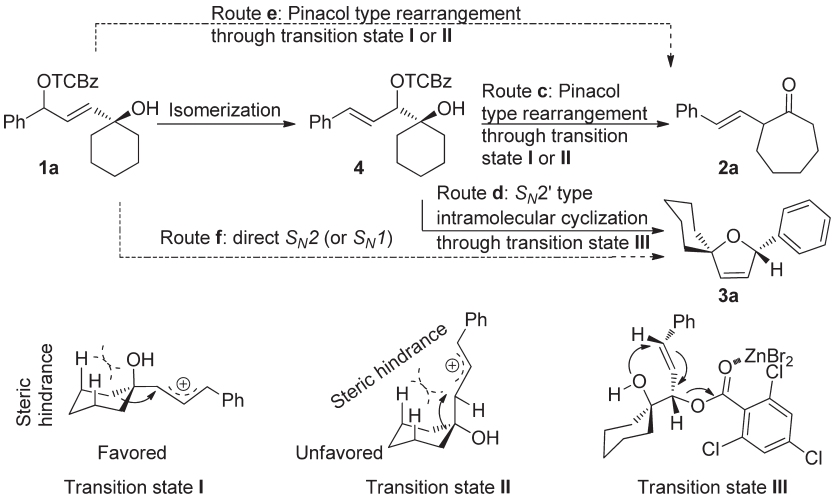
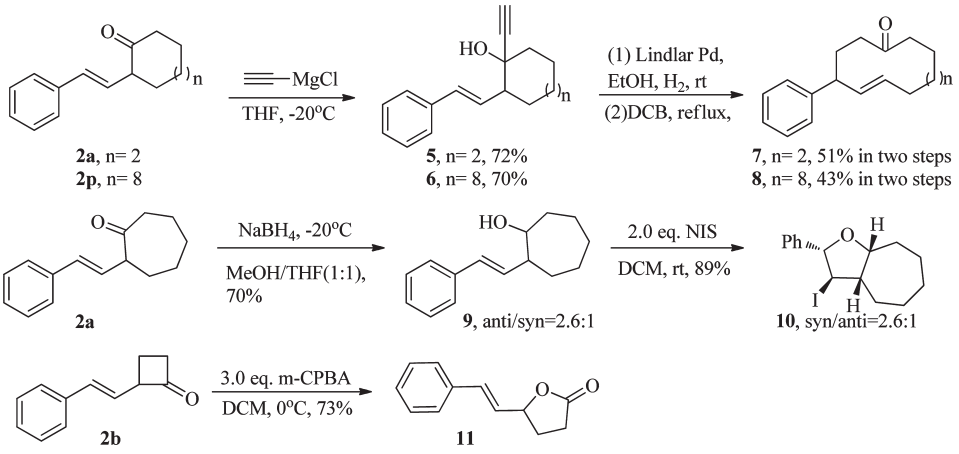
Scheme 4. A Plausible Mechanism



Scheme 5. Further Transformation of Compound 2a, 2p, and 2b



CONCLUSION

In summary, we have developed an efficient gold-catalyzed method to transform cyclic alkanols into one-carbon higher homologated cyclic ketones through an allylic cation-promoted pinacol-type rearrangement, in which various esters, including acetate, benzoate, and electron-deficient 2,4,6-trichlorobenzoate (TCBz), were used as leaving groups. This reaction, coupled with oxy-Cope rearrangement, also provided a new strategy to yield five-carbon homologated ring ketones. In contrast, when 1 mol % of $ZnBr_2$ was utilized, a series of 2,5-dihydrofuran products were obtained in moderate to good yields via a cyclization process.

EXPERIMENTAL SECTION

Typical Procedure for the Gold(I)-Catalyzed Ring Expansion from Allylic Ester Substituted Cycloalkanols 1a. The gold catalyst was generated in an oven-dried Schlenk tube containing a magnetic stirrer bar under N_2 by addition of 0.05 mmol $AuPPh_3Cl$, 0.05 mol $AgSbF_6$, and 2 mL DCM. After the catalyst mixture stirred at room temperature for 2 min, a solution of **1a** (0.1 mmol) in 2 mL DCM was added. The resulting mixture was allowed to stand at 30 °C, until complete consumption of the starting material (as determined by TLC monitoring). The solvent was removed by rotary evaporation, and the residue was purified by column chromatography on silica gel to afford **2a** (81%).

Typical Procedure for the Zinc(II)-Catalyzed Ring Cyclization from Allylic Ester Substituted Cycloalkanols 1a. To a solution of $ZnBr_2$ (1.0 equiv) in 2 mL DCM, was added **1a** (0.1 mmol) in 2 mL DCM under N_2. The resulting mixture was stirred at room temperature. Complete consumption of the starting material was monitored by TLC analysis. The solvent was then removed by rotary evaporation, and the residue was purified by column chromatography on silica gel to afford **3a** (80%).

(*E*)-2-Styrylcycloheptanone 2a.[28] ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.36 (d, J = 7.3 Hz, 2H), 7.30 (t, J = 7.3 Hz, 2H), 7.21 (t, J = 7.2 Hz, 1H), 6.42 (d, J = 16.1 Hz, 1H), 6.31 (dd, J = 16.0, 7.4 Hz, 1H), 3.37−3.32 (m, 1H), 2.62−2.48 (m, 2H), 2.04−1.88 (m, 4H), 1.70−1.62 (m, 2H), 1.48−1.41 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 213.6, 137.1, 130.9, 128.6, 128.5, 127.4, 126.3, 56.3, 42.5, 31.6, 29.7, 28.0, 24.8; IR (neat) 2926, 2854, 1701, 1452, 964, 748, 696 cm^{-1}.

(*E*)-2-Styrylcyclobutanone (2b). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.35 (d, J = 8.0 Hz, 2H), 7.31 (t, J = 7.8 Hz, 2H), 7.25−7.21 (m, 1H), 6.50 (dd, J = 16.0, 1.2 Hz, 1H), 6.22 (dd, J = 16.0, 6.7 Hz, 1H), 4.18−4.10 (m, 1H), 3.21−3.11 (m, 1H), 3.07−2.98 (m, 1H), 2.44−2.34 (m, 1H), 2.09−1.99 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$)

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δ 208.2, 136.7, 131.7, 128.5, 127.6, 126.2, 124.1, 63.1, 45.0, 17.1; IR (neat) 2956, 2922, 1783, 1072, 966, 750, 964 cm^{-1}; HRMS (EI) calcd for $C_{12}H_{12}O$ $[M]^+$ 172.0895, found 172.0882.

(*E*)-2-Styrylcyclopentanone 2c.[29] ^1H NMR (400 MHz, $CDCl_3$) δ 7.34 (d, *J* = 7.3 Hz, 2H), 7.29 (t, *J* = 7.3 Hz, 2H), 7.21 (t, *J* = 7.2 Hz, 1H), 6.47 (d, *J* = 16.0 Hz, 1H), 6.24 (dd, *J* = 16.1, 6.3 Hz, 1H), 2.96 (dd, *J* = 15.9, 8.0 Hz, 1H), 2.42−2.35 (m, 2H), 2.26−2.18 (m, 1H), 2.13−2.07 (m, 1H), 1.96−1.86 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 218.0, 137.0, 132.0, 128.5, 127.4, 126.2, 126.1, 52.4, 37.8, 29.8, 20.8: IR (neat) 2960, 1732, 1647, 1182, 1028, 750, 698 cm^{-1}.

(*E*)-2-styrylcyclohexanone 2d.[4] ^1H NMR (400 MHz, $CDCl_3$) δ 7.31 (d, *J* = 8.0 Hz, 2H), 7.22 (t, *J* = 7.3 Hz, 2H), 7.14 (t, *J* = 7.3 Hz, 1H), 6.37 (dd, *J* = 16.1, 6.5 Hz, 1H), 6.30 (d, *J* = 16.2 Hz, 1H), 3.15−3.09 (m, 1H), 2.41 (td, *J* = 13.6, 4.4 Hz, 1H), 2.33−2.25 (m, 1H), 2.14−2.09 (m, 1H), 2.02−1.95 (m, 1H), 1.89−1.83 (m, 1H), 1.74−1.65 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 211.0, 137.1, 131.4, 128.4, 127.6, 127.3, 126.3, 54.0, 41.7, 34.4, 27.6, 24.4.

(*E*)-2-(4-Methylstyryl)cyclohexanone 2e. ^1H NMR (400 MHz, $CDCl_3$) δ 7.27 (d, *J* = 8.1 Hz, 2H), 7.10 (d, *J* = 7.9 Hz, 2H), 6.41−6.32 (m, 2H), 3.21−3.16 (m, 1H), 2.48 (td, *J* = 13.7, 3.6 Hz, 1H), 2.40−2.35 (m, 1H), 2.32 (s, 3H), 2.21−2.15 (m, 1H), 2.09−2.02 (m, 1H), 1.94−1.90 (m, 1H), 1.81−1.73 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 211.4, 137.1, 134.3, 131.2, 129.2, 126.4, 126.2, 54.1, 41.7, 34.5, 27.6, 24.4, 21.2; IR (neat) 2929, 2858, 1712, 1446, 1124, 966, 792 cm^{-1}; MS (*m*/*z*, rel intensity) 214 (M^+, 100), 143 (23), 129 (28), 115 (14), 105 (37), 91 (11), 77 (5): HRMS (EI) calcd for $C_{15}H_{18}O$ $[M]^+$ 214.1358, found 214.1357.

(*E*)-2-(4-Methoxystyryl)cyclohexanone 2f.[4] ^1H NMR (400 MHz, $CDCl_3$) δ 7.31 (d, *J* = 8.7 Hz, 2H), 6.84 (d, *J* = 8.7 Hz, 2H), 6.33 (d, *J* = 16.1 Hz, 1H), 6.27 (dd, *J* = 16.1, 6.1 Hz, 1H), 3.80 (s, 3H), 3.20−3.14 (m, 1H), 2.48 (td, *J* = 13.8, 3.8 Hz, 1H), 2.39−2.31 (m, 1H), 2.20−2.14 (m, 1H), 2.08−2.02 (m, 1H), 1.95−1.90 (m, 1H), 1.79−1.72 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 211.4, 159.0, 130.8, 130.0, 127.4, 125.3, 113.9, 55.3, 54.0, 41.7, 34.5, 27.6, 24.4; IR (neat) 2933, 2860, 1708, 1606, 1508, 1249, 1174, 1031, 966, 839 cm^{-1}.

(*E*)-2-(4-Fluorostyryl)cyclohexanone 2g. ^1H NMR (400 MHz, $CDCl_3$) δ 7.35 (d, *J* = 8.4 Hz, 1H), 7.33 (d, *J* = 8.4 Hz, 1H), 6.98 (t, *J* = 8.7 Hz, 2H), 6.34−6.33 (m, 2H), 3.20−3.17 (m, 1H), 2.48 (td, *J* = 13.7, 3.6 Hz, 1H), 2.40−2.32 (m, 1H), 2.21−2.16 (m, 1H), 2.11−2.04 (m, 1H), 1.95−1.91 (m, 1H), 1.79−1.72 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 211.1, 162.2 (d, *J* = 245.0 Hz), 133.3, 130.2, 127.7 (d, *J* = 7.9 Hz), 127.3, 115.3 (d, *J* = 21.5 Hz), 53.9, 41.8, 34.4, 27.6, 24.5; IR (neat) 2935, 2864, 1714, 1508, 1226, 966, 850, 804 cm^{-1}; MS (*m*/*z*, rel intensity) 218 (M^+, 100), 174 (36), 146 (34), 122 (77), 109 (31), 95 (3), 81 (13); HRMS (EI) calcd for $C_{14}H_{15}FO$ $[M]^+$ 218.1107, found 218.1110.

(*E*)-2-(4-Fluorostyryl)cycloheptanone 2h. ^1H NMR (400 MHz, $CDCl_3$) δ 7.33 (d, *J* = 8.6 Hz, 1H), 7.31 (d, *J* = 8.6 Hz, 1H), 7.00 (t, *J* = 8.7 Hz, 2H), 6.38 (d, *J* = 16.0 Hz, 1H), 6.22 (dd, *J* = 16.0, 7.6 Hz, 1H), 3.35−3.30 (m, 1H), 2.61−2.48 (m, 2H), 2.03−1.86 (m, 4H), 1.72−1.58 (m, 2H), 1.50−1.40 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 213.7, 162.6 (d, *J* = 245.3 Hz), 133.2, 129.6, 128.3, 127.7 (d, *J* = 7.6 Hz), 115.4 (d, *J* = 21.5 Hz), 56.1, 42.5, 31.6, 30.0, 28.0, 24.8; IR (neat) 2927, 2854, 1701, 1508, 1226, 1157, 1095, 823 cm^{-1}; MS (*m*/*z*, rel intensity) 232 (M^+, 39), 161 (23), 147 (27), 123 (100), 109 (27), 95 (28), 83 (9), 67 (5), 41 (8); HRMS (EI) calcd for $C_{15}H_{17}FO$ $[M]^+$ 232.1263, found 232.1265.

(*E*)-2-(4-Bromostyryl)cycloheptanone 2i. ^1H NMR (400 MHz, $CDCl_3$) δ 7.41 (d, *J* = 8.4 Hz, 2H), 7.22 (d, *J* = 8.4 Hz, 2H), 6.36 (d, *J* = 16.0 Hz, 1H), 6.30 (dd, *J* = 16.0, 6.2 Hz, 1H), 3.36−3.31 (m, 1H), 2.61−2.50 (m, 2H), 2.03−1.86 (m, 4H), 1.72−1.59 (m, 2H), 1.51−1.41 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 213.4, 136.1, 131.6, 129.7, 129.6, 127.8, 121.1, 56.1, 42.6, 31.6, 29.6, 28.1, 24.7; IR (neat) 2926, 2848, 1697, 1487, 1070, 812, 501 cm^{-1}; MS (*m*/*z*, rel intensity) 292 (M^+, 62), 183(89), 181 (100), 128 (45), 95 (10), 77 (4), 67 (3); HRMS (EI) calcd for $C_{15}H_{17}BrO$ $[M]^+$ 292.0463, found 292.0469.

(*E*)-2-(4-Methylstyryl)cycloheptanone 2j. ^1H NMR (400 MHz, $CDCl_3$) δ 7.18 (d, *J* = 7.8 Hz, 2H), 7.03 (d, *J* = 7.9 Hz, 2H), 6.32 (d, *J* = 16.0 Hz, 1H), 6.17 (dd, *J* = 16.0, 7.5 Hz, 1H), 3.28−3.22 (m, 1H), 2.54−2.40 (m, 2H), 2.25 (s, 3H), 1.96−1.80 (m, 4H), 1.65−1.52 (m, 2H), 1.42−1.34 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 213.7, 137.1, 134.3, 130.7, 129.2, 127.5, 126.1, 56.3, 42.4, 31.5, 29.7, 27.9, 24.9, 21.1; IR (neat) 3022, 2923, 2854, 1703, 1452, 966, 808 cm^{-1}; MS (*m*/*z*, rel intensity) 228 (M^+, 14), 119 (100), 91 (26), 65 (6), 41 (4); HRMS (EI) calcd for $C_{16}H_{20}O$ $[M]^+$ 228.1514, found 228.1518.

(*E*)-2-(2-Methylstyryl)cycloheptanone 2k. ^1H NMR (400 MHz, $CDCl_3$) δ 7.44−7.42 (m, 1H), 7.16−7.11 (m, 3H), 6.33 (d, *J* = 15.8 Hz, 1H), 6.18 (dd, *J* = 15.8, 7.7 Hz, 1H), 3.40−3.34 (m, 1H), 2.63−2.49 (m, 2H), 2.33 (s, 3H), 2.05−1.88 (m, 4H), 1.75−1.60 (m, 2H), 1.52−1.38 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 213.6, 136.2, 135.2, 130.1, 130.0, 128.8, 127.3, 126.0, 125.7, 56.6, 42.4, 31.7, 29.7, 27.9, 24.8, 19.7; IR (neat) 2927, 2854, 1708, 1454, 964, 752 cm^{-1}; MS (*m*/*z*, rel intensity) 228 (M^+, 100), 157 (21), 143 (45), 129 (33), 118 (41), 104 (6), 91 (9), 77 (3); HRMS (EI) calcd for $C_{16}H_{20}O$ $[M]^+$ 228.1514, found 228.1516.

(*E*)-2-Styrylcyclooctanone 2m. ^1H NMR (400 MHz, $CDCl_3$) δ 7.35 (d, *J* = 8.0 Hz, 2H), 7.29 (t, *J* = 7.2 Hz, 2H), 7.21 (t, *J* = 7.2 Hz, 1H), 6.44 (d, *J* = 16.0 Hz, 1H), 6.28 (dd, *J* = 16.0, 7.8 Hz, 1H), 3.42−3.36 (m, 1H), 2.54−2.47 (m, 1H), 2.43−2.37 (m, 1H), 2.04−1.82 (m, 4H), 1.76−1.65 (m, 2H), 1.58−1.41 (m, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 217.0, 137.0, 131.1, 128.5, 127.4, 126.2, 55.2, 40.8, 32.6, 27.0, 26.2, 25.9, 24.6; IR (neat) 2921, 2854, 1699, 1446, 966, 748, 696 cm^{-1}; MS (*m*/*z*, rel intensity) 228 (M^+, 80), 143 (40), 129 (100), 117 (22), 115 (32), 104 (67), 91 (29), 65 (3), 41 (5); HRMS (EI) calcd for $C_{16}H_{20}O$ $[M]^+$ 228.1514, found 228.1516.

(*E*)-2-Styrylcyclononanone 2n. ^1H NMR (400 MHz, $CDCl_3$) δ 7.34 (d, *J* = 7.7 Hz, 2H), 7.29 (t, *J* = 7.2 Hz, 2H), 7.21 (t, *J* = 7.1 Hz, 1H), 6.44 (d, *J* = 15.9 Hz, 1H), 6.22 (dd, *J* = 15.9, 8.3 Hz, 1H), 3.49−3.43 (m, 1H), 2.54−2.45 (m, 2H), 2.08−1.99 (m, 1H), 1.95−1.81 (m, 3H), 1.72−1.64 (m, 1H), 1.60−1.54 (m, 3H), 1.48−1.38 (m, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 216.5, 137.0, 131.2, 128.8, 128.5, 127.4, 126.2, 57.3, 41.7, 31.6, 25.7, 25.3, 24.8, 24.5, 24.0; IR (neat) 2930, 2852, 1701, 1450, 946, 748, 695 cm^{-1}; MS (*m*/*z*, rel intensity) 242 (M^+, 51), 340 (5), 143 (32), 129 (100), 115 (26), 104 (38), 91 (23), 77 (7), 41 (5); HRMS (EI) calcd for $C_{17}H_{22}O$ $[M]^+$ 242.1671, found 242.1674.

(*E*)-2-Styrylcyclotridecanone 2o. ^1H NMR (400 MHz, $CDCl_3$) δ 7.35 (d, *J* = 8.1 Hz, 2H), 7.30 (t, *J* = 7.3 Hz, 2H), 7.22 (t, *J* = 7.1 Hz, 1H), 6.46 (d, *J* = 15.8 Hz, 1H), 6.18 (dd, *J* = 15.8, 9.0 Hz, 1H), 3.41 (td, *J* = 9.3, 3.8 Hz, 1H), 2.66 (ddd, *J* = 16.1, 9.2, 3.5 Hz, 1H), 2.42 (ddd, *J* = 16.1, 8.0, 3.7 Hz, 1H), 2.02−1.93 (m, 1H), 1.81−1.72 (m, 1H), 1.60−1.50 (m, 2H), 1.40−1.27 (m, 16H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 212.3, 136.9, 131.6, 128.6, 127.5, 126.2, 56.4, 40.9, 31.8, 26.5, 26.1, 26.0, 25.7, 25.4, 25.1, 24.4, 24.2, 22.8; IR (neat) 2926, 2858, 1708, 1460, 966, 748, 692 cm^{-1}; MS (*m*/*z*, rel intensity) 298 (M^+, 100), 143 (23), 129 (54), 118 (55), 91 (20), 41 (5); HRMS (EI) calcd for $C_{21}H_{30}O$ $[M]^+$ 298.2297, found 298.2299.

2-((1*E*,3*E*)-4-Phenylbuta-1,3-dien-1-yl)cycloheptanone 2p. ^1H NMR (400 MHz, $CDCl_3$) δ 7.34 (d, *J* = 7.6 Hz, 2H), 7.30 (t, *J* = 7.4 Hz, 2H), 7.21 (t, *J* = 7.3 Hz, 1H), 6.75 (dd, *J* = 15.6, 10.4 Hz, 1H), 6.49 (d, *J* = 15.7 Hz, 1H), 6.24 (dd, *J* = 15.3, 10.4 Hz, 1H), 5.90 (dd, *J* = 15.2, 7.6 Hz, 1H), 3.30−3.25 (m, 1H), 2.59−2.46 (m, 2H), 2.01−1.86 (m, 5H), 1.68−1.60 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 213.4, 137.3, 132.6, 131.8, 131.5, 128.7, 128.5, 127.4, 126.2, 56.1, 42.4, 31.4, 29.7, 27.9, 24.8; IR (neat) 2912, 2850, 1703, 1452, 1163, 987, 941, 748, 962 cm^{-1}; HRMS (EI) calcd for $C_{17}H_{20}NaO$ $[M + Na]^+$ 263.1406, found 263.1402.

(1*S*,3*R*, 6*S*,8*S*)-1-((*E*)-Styryl)tricyclo[4.3.1]undecan-2-one 2q. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.38 (d, J = 7.3 Hz, 2H), 7.29 (t, J = 7.3 Hz, 2H), 7.20 (t, J = 7.3 Hz, 1H), 6.41 (d, J = 16.1 Hz, 1H), 6.33 (dd, J = 16.0, 6.7 Hz, 1H), 3.29 (d, J = 6.5 Hz, 1H), 2.84 (t, J = 6.2 Hz, 1H), 2.21−2.18 (m, 2H), 2.05−2.00 (m, 3H), 1.94−1.88 (m, 3H), 1.82−1.76 (m, 3H), 1.72−1.69 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 217.1, 137.3, 131.7, 129.4, 128.4, 127.2, 126.2, 60.8, 49.0, 39.0, 35.4, 33.0, 32.6, 32.0, 31.9, 29.6, 26.9, 26.8; IR (neat) 2912, 2848, 1691, 1446, 1074, 939, 738, 694 cm^{-1}; HRMS (EI) calcd for $C_{19}H_{23}O$ $[M + H]^+$ 267.1743, found 267.1738.

(*E*)-1-Phenylhept-1-en-4-one 2r.[30] ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.37 (d, J = 7.3 Hz, 2H), 7.31 (t, J = 7.3 Hz, 2H), 7.22 (t, J = 7.2 Hz, 1H), 6.47 (d, J = 15.9 Hz, 1H), 6.31 (td, J = 15.7, 7.0 Hz, 1H), 3.31 (d, J = 6.9 Hz, 2H), 2.47 (t, J = 7.3 Hz, 2H), 1.63 (sext, J = 7.4 Hz, 2H), 0.93 (t, J = 7.4 Hz, 3H).

(*E*)-3,5-Diphenylpent-4-en-2-one 2s.[31] ^{1}H NMR (400 MHz, MeOD) δ 7.39−7.36 (m, 4H), 7.32−7.26 (m, 5H), 7.20 (t, J = 7.2 Hz, 1H), 6.65 (dd, J = 15.9, 8.2 Hz, 1H), 6.25 (d, J = 15.9 Hz, 1H), 4.66 (d, J = 8.2 Hz, 1H), 2.14 (s, 3H); ^{13}C NMR (100 MHz, MeOD) δ 207.9, 138.5, 137.0, 132.3, 128.6, 128.1, 128.0, 127.3, 127.2, 127.0, 125.9, 62.4, 27.

(2*R,5*S**)-5-Methyl-2-((*E*)-styryl)cycloheptanone *anti*-2t.** ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.35 (d, J = 7.3 Hz, 2H), 7.29 (d, J = 7.3 Hz, 2H), 7.21 (t, J = 7.2 Hz, 1H), 6.43 (d, J = 16.0 Hz, 1H), 6.25 (dd, J = 16.0, 7.5 Hz, 1H), 3.33−3.27 (m, 1H), 2.66 (td, J = 13.4, 3.3 Hz, 1H), 2.44 (ddd, J = 13.6, 6.0, 2.8 Hz, 1H), 2.05−1.98 (m, 1H), 1.94−1.84 (m, 2H), 1.78−1.67 (m, 1H), 1.63−1.56 (m, 1H), 1.42−1.31 (m, 1H), 1.26−1.13 (m, 1H), 0.98 (d, J = 6.6 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 213., 137.0, 130.9, 128.5, 128.4, 127.4, 126.2, 56.7, 41.2, 36.7, 36.5, 33.2, 30.9, 23.5; IR (neat) 2924, 2868, 1711, 1450, 966, 752, 692 cm^{-1}; MS (m/z, rel intensity) 228 (M^+, 84), 143 (100), 130 (48), 128 (48), 115 (30), 104 (50), 91 (19),77 (5), 41 (4); HRMS (EI) calcd for $C_{16}H_{20}O$ $[M]^+$ 228.1514, found 228.1516.

(2*S,5*S**)-5-Methyl-2-((*E*)-styryl)cycloheptanone *syn*-2t.** ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.38 (d, J = 8.0 Hz, 2H), 7.30 (d, J = 7.8 Hz, 2H), 7.21 (t, J = 7.2 Hz, 1H), 6.41−6.39 (m, 2H), 3.39−3.35 (m, 1H), 2.60−2.57 (m, 2H), 1.99-.94 (m, 2H), 1.90−1.83 (m, 2H), 1.76−1.70 (m, 1H), 1.49−1.40 (m, 2H), 0.97 (d, J = 6.7 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 213.7, 127.2, 131.2, 128.5, 128.2, 127.4, 126.3, 55.3, 40.6, 34.1, 33.8, 31.9, 28.3, 21.4; MS (m/z, rel intensity) 228 (M^+, 100), 143 (71), 130 (42), 128 (41), 115 (23), 104 (21), 91 (5),77 (6); HRMS (EI) calcd for $C_{16}H_{20}O$ $[M]^+$ 228.1514, found 228.1517.

(*E*)-4-Phenylcycloundec-5-enone 7. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.31−7.27 (m, 2H), 7.25−7.23 (m, 2H), 7.18 (tt, J = 7.1, 1.4 Hz, 1H), 5.46 (ddd, J = 15.0, 10.5, 4.6 Hz, 1H), 5.29 (ddd, J = 14.6, 10.1, 1.3 Hz, 1H), 3.11 (ddd, J = 12.5, 10.1, 3.4 Hz, 1H), 2.71−2.61 (m, 2H), 2.50 (q, J = 12.8 Hz, 1H), 2.28 (dd, J = 15.7, 7.7 Hz, 1H), 2.22−2.14 (m, 2H), 1.92−1.83 (m, 1H), 1.81−1.73 (m, 1H), 1.71−1.63 (m, 3H), 1.45−1.35 (m, 1H), 1.14−1.02 (m, 2H) ; ^{13}C NMR (100 MHz, $CDCl_3$) δ 211.1, 145.0, 134.7, 130.8, 128.5, 126.9, 126.1, 52.5, 42.6, 40.6, 34.0, 30.4, 25.7, 24.4, 24.3; IR (neat)3026, 2926, 2852, 1708, 1438, 974, 752, 698 cm^{-1}; MS (m/z, rel intensity) 242 (M^+, 20), 224 (100), 143 (42), 129 (61), 91 (26), 77 (5), 41(3); HRMS (EI) calcd for $C_{17}H_{22}O$ $[M]^+$ 242.1671, found 242.1673.

(*E*)-4-Phenylcycloheptadec-5-enone 8. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.29 (t, J = 7.4 Hz, 2H), 7.23−7.16 (m, 3H), 5.52−5.43 (m, 2H), 3.22−3.17 (m, 1H), 2.55−2.45 (m, 2H), 2.43−2.32 (m, 2H), 2.14−1.91 (m, 5H), 1.67−1.62 (m, 2H), 1.39−1.29 (m, 15H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 211.8, 145.1, 133.3, 131.5, 128.4, 127.1, 126.1, 48.4, 42.6, 41.0, 31.8, 30.1, 29.6, 28.7, 27.9, 27.7, 27.6, 27.2, 26.9, 23.9; IR (neat) 3026, 2926, 2854, 1710, 1452, 968, 756, 698 cm^{-1}; MS (m/z, rel intensity) 326 (M^+, 47), 157 (22), 143 (100), 129 (68), 91 (34), 77 (3), 41 (13); HRMS (EI) calcd for $C_{23}H_{34}O$ $[M]^+$ 326.2610, found 326.2607.

(2*S,3*R**,3a*S**,8a*R**)-3-Iodo-2-phenyloctahydro-2*H*-cyclohepta[*b*]furan 10.** ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.45 (dd, J = 8.0, 1.6 Hz, 2H), 7.38−7.30 (m, 3H), 4.89 (d, J = 9.7 Hz, 1H), 4.28 (td, J = 10.0, 3.6 Hz, 1H), 3.56 (t, J = 9.6 Hz, 1H), 2.78−2.70 (m, 1H), 2.10−2.00 (m, 2H), 1.90−1.73 (m, 4H), 1.52−1.43 (m, 1H), 1.41−1.26 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 137.9, 128.4, 128.3, 126.9, 88.0, 82.2, 54.9, 36.4, 32.1, 31.2, 28.4, 27.4, 25.0; IR (neat) 2922, 2850, 1452, 1039, 1024, 758, 696 cm^{-1}; MS (m/z, rel intensity) 342 (M^+, 2), 215 (100), 129 (22), 105 (48), 91 (22), 77 (8), 41 (4); HRMS (EI) calcd for $C_{15}H_{19}IO$ $[M]^+$ 342.0481, found 342.0482.

(*E*)-5-Styryldihydrofuran-2(3*H*)-one 11.[17a] ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40 (d, J = 7.8 Hz, 2H), 7.34 (t, J = 8.0 Hz, 2H), 7.28 (t, J = 7.1 Hz, 1H), 6.69 (d, J = 15.9 Hz, 1H), 6.20 (dd, J = 15.9, 6.6 Hz, 1H), 5.12 (td, J = 14.6, 7.9 Hz, 1H), 2.66−2.56 (m, 2H), 2.54−2.45 (m, 1H), 2.15−2.06 (m, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 176.8, 135.6, 132.8, 128.7, 128.4, 126.7, 126.4, 80.6, 28.9, 28.5.

2-Phenyl-1-oxaspiro[4.5]dec-3-ene 3a. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.27−7.17 (m, 5H), 5.94−5.92 (m, 1H), 5.72−5.70 (m, 2H), 1.67−1.60 (m, 5H), 1.49−1.35 (m, 5H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 142.4, 133.9, 129.0, 128.4, 127.5, 126.5, 90.2, 86.4, 38.3, 37.4, 25.5, 23.6, 23.3; IR (neat) 2958, 2946, 2854, 1448, 1259, 1085, 1062, 1041, 1022, 800, 696 cm^{-1}; HRMS (EI) calcd for $C_{15}H_{19}O$ $[M + H]^+$ 215.1430, found 215.1426.

2-(4-Fluorophenyl)-1-oxaspiro[4.5]dec-3-ene 3h. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.29 (t, J = 7.6 Hz, 2H), 7.01 (t, J = 8.6 Hz, 2H), 6.02 (d, J = 4.0 Hz, 1H), 5.76−5.74 (m, 2H), 1.73−1.64 (m, 5H), 1.56−1.47 (m, 5H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 162.6 (d, J = 234.9 Hz), 138.2, 134.2, 128.8, 128.2 (d, J = 8.0 Hz), 115.2 (d, J = 21.3 Hz), 90.2, 85.7, 38.4, 37.3, 25.4, 23.5, 23.3; IR (neat) 2946, 2852, 1508, 1220, 1068, 1041, 835, 825, 792 cm^{-1}; HRMS (EI) calcd for $C_{15}H_{18}FO$ $[M + H]^+$ 233.1336, found 233.1335.

2-(4-Bromophenyl)-1-oxaspiro[4.5]dec-3-ene 3i. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.45 (d, J = 7.7 Hz, 2H), 7.21 (d, J = 7.7 Hz, 2H), 6.02−6.01 (m, 1H), 5.80−5.75 (m, 2H), 1.76−1.64 (m, 6H), 1.55−1.44 (m, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 141.6, 134.4, 131.4, 128.5, 128.1, 121.3, 90.4, 85.7, 38.3, 37.3, 25.4, 23.5, 23.3; IR (neat) 3076, 2946, 2854, 1487, 1446, 1068, 1047, 1010, 846, 817, 777, 725 cm^{-1}; HRMS (EI) calcd for $C_{15}H_{18}BrO$ $[M + H]^+$ 293.0536, found 293.0545.

2-(*p*-Tolyl)-1-oxaspiro[4.5]dec-3-ene 3j. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.23 (d, J = 8.0 Hz, 2H), 7.15 (d, J = 7.9 Hz, 2H), 6.01 (dd, J = 6.2, 2.7 Hz, 1H), 5.78−5.77 (m, 2H), 2.34 (s, 3H), 1.78−1.74 (m, 4H), 1.71−1.65 (m, 2H), 1.54−1.44 (m, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 139.5, 137.1, 133.8, 129.1, 129.0, 126.5, 90.0, 86.2, 38.4, 37.4, 25.5, 23.6, 23.3, 21.1; IR (neat) 2946, 2854, 1512, 1445, 1083, 1070, 1049, 1041, 1020, 815, 779 cm^{-1}; HRMS (EI) calcd for $C_{16}H_{21}O$ $[M + H]^+$ 229.1587, found 229.1582.

2-(*o*-Tolyl)-1-oxaspiro[4.5]dec-3-ene 3k. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.43 (d, J = 7.3 Hz, 1H), 7.22−7.12 (m, 3H), 6.04−6.03 (m, 1H), 6.00 (dd, J = 6.0, 2.4 Hz, 1H), 5.83 (dd, J = 5.9, 1.3 Hz, 1H), 2.38 (s, 3H), 1.83−1.62 (m, 6H), 1.53−1.42 (m, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 140.3, 134.6, 134.0, 130.1, 128.1, 127.1, 126.2, 126.0, 89.8, 83.1, 38.1, 37.3, 25.5, 23.6, 23.3, 19.1; IR (neat) 3020, 2946, 2854, 1448, 1267, 1068, 1043, 748, 713 cm^{-1}; HRMS (EI) calcd for $C_{16}H_{21}O$ $[M + H]^+$ 229.1587, found 229.1582.

2-Phenyl-1-oxaspiro[4.6]undec-3-ene 3m. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.33−7.31 (m, 4H), 7.28−7.35 (m, 1H), 5.99−5.97 (m, 1H), 5.74−5.71 (m, 2H), 1.98−1.93 (m, 2H), 1.78−1.68 (m, 5H), 1.66−1.59 (m, 2H), 1.53−1.46 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 142.2, 135.6, 128.3, 128.0, 127.5, 126.6, 93.6, 86.2, 41.3, 40.0, 29.6, 23.0, 22.9; IR (neat) 2946, 2852, 1454, 1085, 1045, 1028, 752, 696 cm^{-1}; HRMS (EI) calcd for $C_{16}H_{21}O$ $[M]^+$ 229.1587, found 229.1583.

2-Phenyl-1-oxaspiro[4.7]dodec-3-ene 3n. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.33−7.32 (m, 4H), 7.29−7.24 (m, 1H), 6.02 (dd, J = 6.2, 2.8 Hz, 1H), 5.75−5.73 (m, 2H), 2.10−2.03 (m, 1H), 1.99−1.93 (m, 1H), 1.88−1.82 (m, 1H), 1.78−1.58 (m, 8H), 1.52−1.47 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 142.6, 135.0, 128.5, 128.3, 127.5, 126.6, 93.4, 86.2, 36.6, 35.6, 28.4, 28.2, 24.9, 22.7, 22.6; IR (neat) 2946, 2850, 1456, 1082, 1066, 1028, 696 cm^{-1}; HRMS (EI) calcd for $C_{17}H_{23}O$ $[M + H]^+$ 243.1743, found 243.1741.

2-Phenyl-1-oxaspiro[4.11]hexadec-3-ene 3o. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.36−7.31 (m, 4H), 7.28−7.24 (m, 1H), 5.97 (dd, J = 6.0, 2.4 Hz, 1H), 5.75−5.73 (m, 2H), 1.85−1.76 (m, 2H), 1.74−1.66 (m, 1H), 1.63−1.59 (m, 1H), 1.51−1.47 (m, 4H), 1.40−1.35 (m, 14H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 142.3, 134.5, 128.5, 128.3, 127.5, 126.5, 93.3, 86.6, 34.8, 33.9, 26.5, 26.0, 22.6, 22.2, 20.3, 19.7; IR (neat) 2946, 2848, 1469, 1446, 1058, 1041, 1016, 746, 696 cm^{-1}; HRMS (EI) calcd for $C_{21}H_{31}O$ $[M + H]^+$ 299.2369, found 299.2371.

(1*R,2*R**,5*S**)-5′-Phenyl-5*H*-spiro[adamantane-2,2′-furan] 3q.** ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.35−7.30 (m, 4H), 7.28−7.23 (m, 1H), 6.34 (dd, J = 5.8, 2.2 Hz, 1H), 5.84−5.81 (m, 2H), 2.30 (d, J = 12.2 Hz, 2H), 1.92−1.74 (m, 10H), 1.61 (d, J = 12.4 Hz, 2H) ; ^{13}C NMR (100 MHz, $CDCl_3$) 142.9, 132.5, 129.9, 128.2, 127.3, 126.2, 94.1, 86.2, 39.2, 38.6, 37.9, 35.9, 35.7, 33.9, 33.2, 27.6, 26.8;δ IR (neat) 2945, 2849, 1452, 1043, 1040, 1021, 749, 696 cm^{-1}; HRMS (EI) calcd for $C_{19}H_{23}O$ $[M + H]^+$ 267.1743, found 267.1739.

■ ASSOCIATED CONTENT

Supporting Information. Experimental procedures and data for all new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

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■ REFERENCES

(1) (a) Khumtaveeporn, K.; Alper, H. *Acc. Chem. Res.* **1995**, *28*, 414. (b) Dowd, P.; Zhang, W. *Chem. Rev.* **1993**, *93*, 2091. (c) Dowd, P.; Zhang, W. *Chem. Rev.* **1994**, *94*, 565.

(2) For some recent examples, see: (a) George, J. H.; Baldwin, J. E.; Adlington, R. M. *Org. Lett.* **2010**, *12*, 2394. (b) Overman, L. E.; Tanis, P. S. *J. Org. Chem.* **2010**, *75*, 455. (c) Frongia, A.; Girard, C.; Ollivier, J.; Piras, P. P.; Secci, F. *Synlett* **2008**, 2823. (d) Tang, J.-M.; Bhunia, S.; Sohel, S. M. A.; Lin, M.-Y.; Liao, H.-Y.; Datta, S.; Das, A.; Liu, R.-S. *J. Am. Chem. Soc.* **2007**, *129*, 15677. (e) Suzuki, K.; Takikawa, H.; Hachisu, Y.; Bode, J. W. *Angew. Chem., Int. Ed.* **2007**, *46*, 3252.

(3) For examples for allylic cation induced ring expansion of cyclopropanols, see: (a) Ollivier, J.; Legros, J.-Y.; Fiaud, J.-C.; de Meijere, A.; Salaün, J. *Tetrahedron Lett.* **1990**, *31*, 4135. (b) Ollivier, J.; Salaün, J. *Tetrahedron Lett.* **1984**, *25*, 1269. (c) Salaün, J.; Karkour, B. *Tetrahedron Lett.* **1988**, *29*, 1537. (d) Funayama, S.; Eda, S.; Komiyama, K.; Ohmura, S.; Tokunaga, T. *Tetrahedron Lett.* **1989**, *30*, 3151. (e) Salaün, J.; Karkour, B. *Tetrahedron Lett.* **1987**, *28*, 4669. (f) Lutz, R. E.; Bass, R. G.; Boykin, D. W., Jr. *J. Org. Chem.* **1964**, *29*, 3660. (g) Wiesner, K.; Ho, P.-T.; Ohtani, H. *Can. J. Chem.* **1974**, *52*, 640.

(4) A recent example for Pd/Cu catalyzed ring expansion of 1,4-allylic diol derivative, which worked only in four- or five-membered substrates:Lange, A.; Heydenreuter, W.; Menz, H.; Kirsch, S. F. *Synlett* **2009**, 2987.

(5) Recent reviews on gold catalysis: (a) Hashmi, A. S. K. *Chem. Rev.* **2007**, *107*, 3180. (b) Fürstner, A.; Davies, P. W. *Angew. Chem., Int. Ed.* **2007**, *46*, 3410. (c) Li, Z.; Brouwer, C.; He, C. *Chem. Rev.* **2008**, *108*, 3239. (d) Arcadi, A. *Chem. Rev.* **2008**, *108*, 3266. (e) Jimenez-Nunez, E.; Echavarren, A. M. *Chem. Rev.* **2008**, *108*, 3326. (f) Gorin, D. J.; Sherry, B. D.; Toste, F. D. *Chem. Rev.* **2008**, *108*, 3351. (g) Fürstner, A. *Chem. Soc. Rev.* **2009**, *38*, 3208. (h) Nevado, C. *Chimia* **2010**, *64*, 247. (i) Hashmi, A. S. K. *Angew. Chem., Int. Ed.* **2010**, *49*, 5232. A recent review on gold-catalyzed ring expansions: (j) Garayalde, D.; Nevado, C. *Beilstein J. Org. Chem.* **2011**, *7*, 767.

(6) The first gold-catalyzed ring expansion example was described by Hashmi group, which focused on the ring expansion of the heterocyclic epoxide: Hashmi, A. S. K.; Sinha, P. *Adv. Synth. Catal.* **2004**, *346*, 432.

(7) (a) Markham, J. P.; Staben, S. T.; Toste, F. D. *J. Am. Chem. Soc.* **2005**, *127*, 9708. (b) Kleinbeck, F.; Toste, F. D. *J. Am. Chem. Soc.* **2009**, *131*, 9178.

(8) Ye, S. Y.; Yu, Z.-X. *Org. Lett.* **2010**, *12*, 804.

(9) Li, C.-W.; Pati, K.; Lin, G.-Y.; Sohel, S. M. A.; Hung, H.-H.; Liu, R.-S. *Angew. Chem., Int. Ed.* **2010**, *49*, 9891.

(10) Other examples of gold-catalyzed ring-opening or ring-expansion reactions: (a) Lee, S. I.; Baek, J. Y.; Sim, S. H.; Chung, Y. K. *Synthesis* **2007**, 2107. (b) Garayalde, D.; Gómez-Bengoa, E.; Huang, X.; Goeke, A.; Nevado, C. *J. Am. Chem. Soc.* **2010**, *132*, 4720. (c) Mauleón, P.; Krinsky, J. L.; Toste, F. D. *J. Am. Chem. Soc.* **2009**, *131*, 4513.

(11) Chen, A.; Lin, R.; Liu, Q.; Jiao, N. *Chem. Commun.* **2009**, 6842.

(12) (a) Trost, B. M.; Yasukata, T. *J. Am. Chem. Soc.* **2001**, *123*, 7162. (b) Trost, B. M.; Xie, J.; Maulide, N. *J. Am. Chem. Soc.* **2008**, *130*, 17258.

(13) Xu, H.-D.; Zhang, W.; Shu, D. X.; Werness, J. B.; Tang, W. P. *Angew. Chem., Int. Ed.* **2008**, *47*, 8933.

(14) (a) Iwasawa, N.; Matsuo, T.; Iwamoto, M.; Ikeno, T. *J. Am. Chem. Soc.* **1998**, *120*, 3903. (b) Iwasawa, N.; Narasaka, K. *Top. Curr. Chem.* **2000**, *207*, 69.

(15) Shi, M.; Liu, L.-P.; Tang, J. *J. Am. Chem. Soc.* **2006**, *128*, 7430.

(16) Furstner., A.; Aïssa, C. *J. Am. Chem. Soc.* **2006**, *128*, 6306.

(17) (a) Wang, Y. H.; Zhu, L. L.; Zhang, Y. X.; Chen, Z. *Chem. Commun.* **2010**, *46*, 577. (b) Chen, Z.; Zhang, Y.-X.; Wang, Y.-H.; Zhu, L.-L.; Liu, H.; Li, X.-X.; Guo, L. *Org. Lett.* **2010**, *12*, 3468. (c) Zhu, L.-L.; Wang, Y.-H.; Zhang, Y.-X.; Li, X.-X.; Liu, H.; Chen, Z. *J. Org. Chem.* **2011**, *76*, 441.

(18) For selected reviews, see: (a) Faul, M. M.; Huff, B. E. *Chem. Rev.* **2000**, *100*, 2407. (b) Fernandez, J. J.; Souto, M. L.; Norte, M. *Nat. Prod. Rep.* **2000**, *23*, 26. (c) Blunt, J. W.; Copp, B. R.; Munro, M. H. G.; Northcote, P. T.; Prinsep, M. R. *Nat. Prod. Rep.* **2006**, *17*, 235.

(19) Gold-catalyzed Prins cyclizations: Jimenez-Nunez, E.; Claverie, C. K.; Nieto-Oberhuber, C.; Echavarren, A. M. *Angew. Chem., Int. Ed.* **2006**, *45*, 5452.

(20) An inseparable mixture might include different elimination products and/or their further dervatives.

(21) For the detailed reaction condition optimization and the mechanistic explanation for the reaction in eq 4, Scheme 2, see Supporting Information for the details.

(22) In the transformation of cyclohexanols, when TCBz was used as the protecting group in electron rich arene substrates, the yield was very low.

(23) Compound **4** can be detected by TLC in the reaction of **1a**, in either the gold-catalyzed or $ZnBr_2$-mediated reaction. If **1a**'s reaction was halted by the addition of water in the condition of $AuPPh_3Cl$/$AgSbF_6$ (5 mol %), product **4** can be separated from the reaction mixture. Therefore, it is a possible reaction intermediate.

(24) Examples for the tricoordinated gold(I) species: (a) Zeng, X.; Soleilhavoup, M.; Bertrand, G. *Org. Lett.* **2009**, *11*, 3166. (b) Lavallo, V.; Frey, G. D.; Donnadieu, B.; Soleilhavoup, M.; Bertrand, G. *Angew. Chem., Int. Ed.* **2008**, *47*, 5224.

(25) Some recent examples of chirality transfer in gold-catalyzed reactions: (a) Wang, D.-W.; Gautam, L. N. S.; Bollinger, C.; Harris, A.;

Li, M.-Y.; Shi, X.-D. *Org. Lett.* **2011**, *13*, 2618. (b) Kawai, N.; Abe, R.; Uenishi, J. *Tetrahedron Lett.* **2009**, *50*, 6580. (c) Lo, V. K.-Y.; Wong, M.-K.; Che, C.-M. *Org. Lett.* **2008**, *10*, 517. (d) Nakamura, I.; Sato, T.; Terada, M.; Yamamoto, Y. *Org. Lett.* **2008**, *10*, 2649. (e) Yang, C.-Y.; Lin, G.-Y.; Liao, H.-Y.; Datta, S.; Liu, R.-S. *J. Org. Chem.* **2008**, *73*, 4907. (f) Volz, F.; Krause, N. *Org. Biomol. Chem.* **2007**, *5*, 1519. (g) Aponick, A.; Biannic, B. *Org. Lett.* **2011**, *13*, 1330. (h) Mukherjee, P.; Widenhoefer, R. A. *Org. Lett.* **2011**, *13*, 1334.

(26) 2,5-Dihydrofuran has ever been assumed to be the reaction intermediate to give rearrangement products in acid-catalyzed rearrangement of the vinylogous benzopinacol; see ref 3f.

(27) Janardhanam, S.; Devan, B.; Rajagopalan, R. *Tetrahedron Lett.* **1993**, *34*, 6761.

(28) Katritzky, A. R.; Toader, D.; Xie, L. *J. Org. Chem.* **1996**, *61*, 7571.

(29) Ohe, T.; Ohse, T.; Mori, K.; Ohtaka, S.; Uemura, S. *Bull. Chem. Soc. Jpn.* **2003**, *76*, 1823.

(30) Obora, Y.; Ogawa, Y.; Imai, Y.; Kawamura, T.; Tsuji, Y. *J. Am. Chem. Soc.* **2001**, *123*, 10489.

(31) Dai, W.; Yeung, K.; Liu, J.; Zhang, Y.; Williams, L. D. *Org. Lett.* **2002**, *4*, 1615.