

Dual Visible Light Photoredox and Gold-Catalyzed Arylative Ring Expansion

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Supporting Information

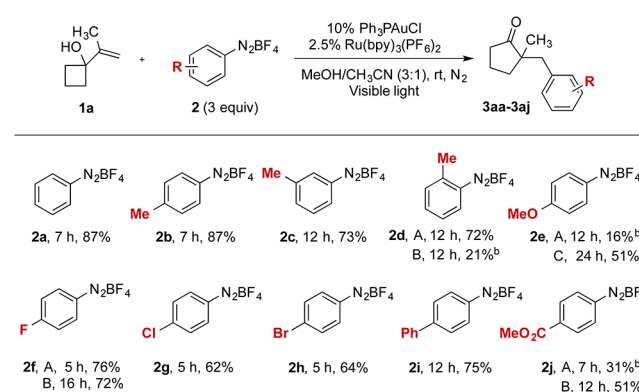
ABSTRACT: A combination of visible light photocatalysis and gold catalysis is applied to a ring expansion–oxidative arylation reaction. The reaction provides an entry into functionalized cyclic ketones from the coupling reaction of alkenyl and allenyl cycloalkanols with aryl diazonium salts. A mechanism involving generation of an electrophilic gold(III)–aryl intermediate is proposed on the basis of mechanistic studies, including time-resolved FT-IR spectroscopy.

Homogeneous gold catalysis has received great attention in the past decade.¹ The majority of reports rely on the π -acidity of either gold(I) or gold(III) complexes to activate multiple bonds toward nucleophilic attack, followed by protodeauration. On the other hand, gold complexes, in combination with a strong oxidant, have been shown to catalyze oxidative functionalization reactions of unactivated alkenes.^{2,3} In general, these reactions are proposed to proceed through alkylgold(III) intermediates that undergo coupling with nucleophiles such as arylsilanes and boronic acids.⁴ Recently, Glorius and co-workers proposed that aryl radicals, generated by photoredox reaction of aryldiazonium salts, could be employed to access analogous gold(III) species through oxidation of an alkylgold(I) intermediate (A, eq 1).⁵ As an

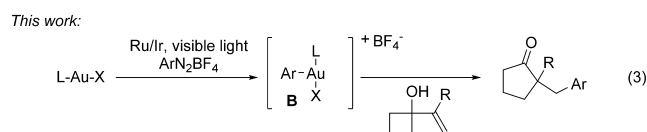
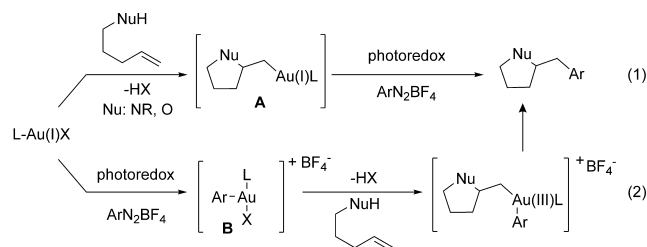
(B) that subsequently reacts with the alkene to induce intramolecular heteroarylation (eq 2). Inspired by recent reports from the Gaunt laboratory,⁷ we hypothesized that gold(III) species B might be a potent electrophile, capable of engaging π -bonds and ultimately delivering a formal aryl electrophile (eq 3). Herein, we describe application of this hypothesis to the development of a gold-catalyzed arylative ring expansion and experiments distinguishing these mechanistic paths.

On the basis of this hypothesis, we reacted vinylcyclopropanol (1a) and phenyldiazonium 2a with 10% triphenylphosphinegold(I) and 5% Ru(bpy)₃(PF₆)₂ under visible light.⁸ Under these conditions, 1a underwent ring expansion⁹ and coupling¹⁰ with 2a to afford cyclopentanone 3aa in 87% yield (Scheme 1, 2a). Only a trace amount of product was detected by NMR when the reaction was conducted in the absence of light, photocatalyst, or gold catalyst (Table S3). The reaction proceeded smoothly with diazonium salts having methyl

Scheme 1. Reaction of 1a with Diazonium Compounds^a



^aUnless noted otherwise, method A was used: visible light, 1a (0.2 mmol), ArN₂BF₄ (3 equiv), Ph₃PAuCl (10 mol%), Ru(bpy)₃(PF₆)₂ (2.5 mol%), degassed MeOH/CH₃CN (3:1, 5 mL) under N₂ at rt. Method B was used: Ph₃PAuCl (10 mol%), Ir(ppy)₃ (2.5 mol%). Method C was used: (4-CF₃Ph)₃PAuCl (10 mol%), Ru(bpy)₃(PF₆)₂ (2.5 mol%). Isolated yields are given. ^bYields were calculated on the basis of ¹H NMR using internal standard.



alternative, we envisioned that these reactions might proceed through a pathway in which photoredox catalysis⁶ occurs first, providing an entry into a cationic arylgold(III) intermediate

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substituted at each position of the aryl ring, giving good yields of desired products **2b–d**. However, a more electron-rich substituent on the aryl ring gave low yield with the use of Ph_3PAuCl as catalyst. A strong electron-withdrawing group on the ligand of the gold catalyst improved the yield of desired product (**2e**, method A vs C). The arylation of electron-deficient diazoniums also proceeded efficiently in the presence of Ru catalyst (**2f–j**). In the case of $\text{Ir}(\text{ppy})_3$ -catalyzed arylation of **2d**, a lower yield of desired product was obtained in 12 h, and a significant amount of diazonium salt was recovered (**2d**, method A vs B). However, improved results were obtained when the Ir photocatalyst was employed to couple electron-poor diazonium salts (**2f** and **2j**, method A vs B).

The reaction proceeded efficiently with various alkyl-substituted alkenes (Table 1, entries 1–3). A substrate bearing

Table 1. Scope Studies of Vinylcyclobutanols and Vinylcyclopropanols^a

1, n = 1, 2 2, Ar = Ph, 4-FPh 3

entry	n	R	Ar	time (h)	3 (% yield)
1	2	n-hexyl (1b)	Ph	6	3ba (90)
2	2	isopropyl (1c)	Ph	6	3ca (81)
3	2	Bn (1d)	Ph	6	3da (83)
4	2	PhthN(CH ₂) ₃ (1e)	Ph	4	3ea (80)
5	2	Ph (1f)	Ph	24	3fa (34)
6 ^b	2	Ph (1f)	4-FPh	24	3fb (71)
7 ^b	2	4-ClPh (1g)	4-FPh	24	3ga (67)
8 ^b	2	4-MePh (1h)	4-FPh	6	3ha (80)
9 ^b	2	2-MePh (1i)	4-FPh	24	3ia (32)
10	1	Ph (1j)	Ph	15	3ja (67)
11	1	Bn (1k)	Ph	6	3ka (51)

^aUnless noted otherwise, method A was used (see Scheme 1, footnote a). Isolated yields are given. ^bMethod D was used: 4-FPhN₂BF₄ (4 equiv), $\text{Ir}(\text{ppy})_3$ (2.5 mol%), and (4-CF₃Ph)₃PAuCl (10 mol%).

a protected amine group was tolerated (entry 4). The Ru catalyst was inefficient in promoting the reaction of aryl-substituted substrates, and product **3faa** was obtained in low yield with significant decomposition (entry 5); however, use of the Ir catalyst improved the reaction (entries 6–8).¹¹ The reactivity was decreased when a sterically hindered aryl group was used (entry 9). Finally, good yields of cyclobutanones were obtained from the ring expansion/coupling reaction of vinylcyclopropanols (entries 10 and 11).

To probe the mechanism of this dual catalysis, time-resolved FT-IR spectroscopy in the attenuated total reflection (ATR) mode was employed to detect intermediates under reaction conditions. Catalysis in methanol/acetonitrile (3/1) solution containing reactants **1a** and **2b**, catalyst (CF₃Ph)₃PAuCl, and sensitizer $\text{Ru}(\text{bpy})_3(\text{PF}_6)_2$ held in a liquid cell was initiated with a 458 nm laser pulse (150 mW, Ar ion laser) of 12 s duration. Arrival of the laser pulse was synchronized with the acquisition of rapid-scan FT-IR spectra over a period of 96 s. Reaction of the phenyl radical generated by photoactivation of the sensitizer was monitored by characteristic infrared absorptions of the reactants and final cyclopentanone product, which were identified by recording spectra of authentic samples (compound **2b**, 1583 cm⁻¹, $\nu_{\text{Ar}(\text{C}-\text{C})}$; compound **1a**, 1467 cm⁻¹, $\nu_{(\text{C}=\text{C})}$ and 1250 cm⁻¹, $\nu_{(\text{C}-\text{O})}$; additional spectral data are

presented in Table S5 and Figure S7). The kinetic behavior for the formation of the final product **3ab** (phenyl C–C mode at 1515 cm⁻¹) displays an induction period relative to the kinetics for consumption of the diazonium compound and suggests the formation of an intermediate involved in the rate-limiting step. As shown in Figure 1, the absorption band at 1488 cm⁻¹ was

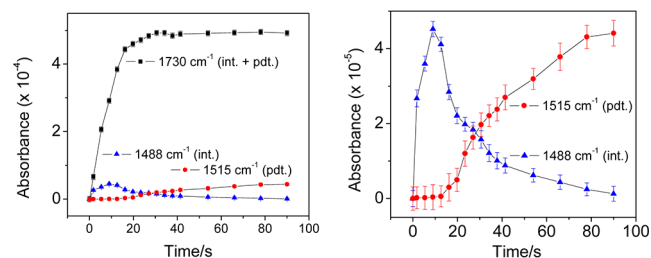
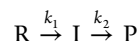


Figure 1. Temporal behavior of intermediate (1488 cm⁻¹) and final product (1515 cm⁻¹) of arylation–ring expansion of vinylcyclobutanol in liquid solution monitored by rapid-scan ATR FT-IR spectroscopy. The panel on the right shows the temporal behavior on an expanded absorbance scale for clarity. The band at 1730 cm⁻¹ is the C=O mode of the expanded ring.

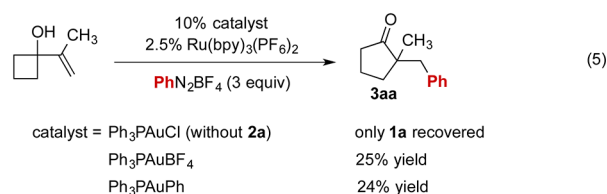
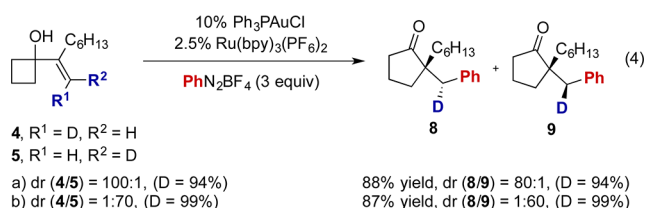
identified to be associated with this intermediate, increasing upon onset of the light pulse and decreasing concurrently with the growth of the final product. The kinetic relevancy of this intermediate was directly demonstrated by the matching rates of its consumption and the rise of the product band at 1515 cm⁻¹. The absorption band at 1730 cm⁻¹, which is the $\nu_{(\text{C}=\text{O})}$ mode of the expanded ring, is also associated with this intermediate. By simultaneous least-squares fitting of the temporal behavior of the 1250 cm⁻¹ reactant, the 1488 cm⁻¹ intermediate, and the 1515 cm⁻¹ final product bands according to the model



kinetic parameters were obtained, on the basis of which the temporal behavior of the 1730 cm⁻¹ C=O stretch absorption was simulated. As shown in Figure S8, excellent agreement of the simulated curve with the experimental absorbance at 1730 cm⁻¹ was obtained. The result confirms that both the intermediate and the final product absorb at 1730 cm⁻¹. Notably, these bands were not observed when the experiment was carried out in the absence of gold (Figure S7), strongly suggesting that the gold catalyst is required for ring expansion to occur. These observations are consistent with a kinetically relevant intermediate that requires decomposition of the diazonium compound for its formation and contains an expanded five-membered-ring ketone (1730 cm⁻¹), but has yet to undergo reductive elimination to form the C–C bond (methyl-substituted analogue of **11**, see Scheme 2).

The stereochemical course of the gold-catalyzed ring expansion–arylation reaction was probed with deuterium-labeled alkenes (eq 4). In the presence of gold catalysts, the ring expansion reaction occurred with high levels of stereospecificity.¹² Moreover, the observed stereochemistry of the corresponding products is consistent with the previously observed *anti*-migration¹³ and carbon–carbon bond formation with stereochemical retention from alkylgold(III)–phenyl species.^{4a}

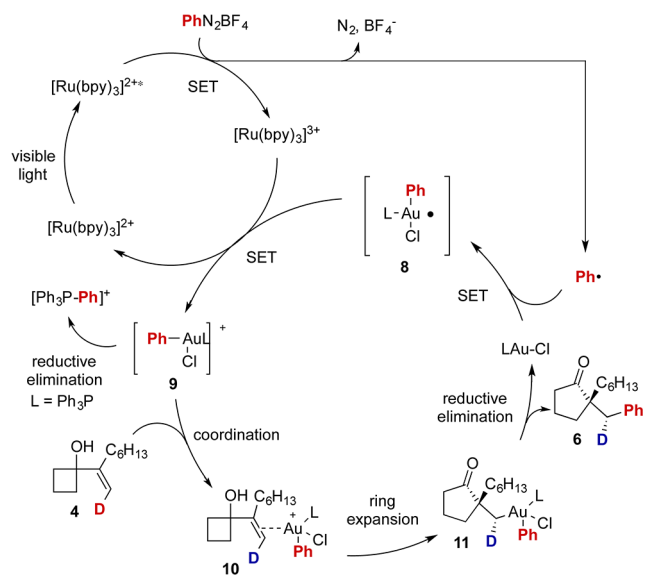
The current ring expansion–arylation reaction appears to begin with gold(III) or gold(I) coordination with the alkene. However, Ph_3PAuCl on its own does not promote additions to



alkenes, and employing Ph₃PAuBF₄ as catalyst produced inferior results (eq 4 and Figure S6). The reaction of Ph₃PAuCl with phenyl radical could generate Ph₃PAuPh,¹⁴ which would catalyze the title reaction. However, employing the independently prepared phenylgold(I) compound as a catalyst produced 3aa in inferior yield (eq 5).

On the basis of these observations and the experimental results described above, a possible mechanism is proposed in Scheme 2. The reaction of PhN₂BF₄ with photoexcited

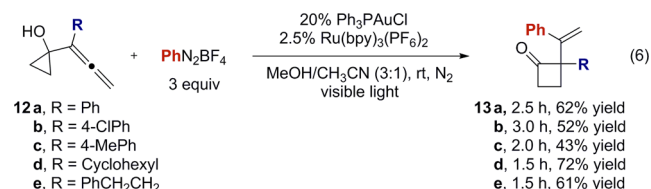
Scheme 2. Proposed Mechanism for Photoredox-Promoted, Gold-Catalyzed Ring Expansion–Arylation Reaction



Ru(bpy)₃^{2+*} generates Ru(bpy)₃³⁺ and phenyl radical, and that reacts with the gold(I) catalyst to initially generate gold(II)–aryl 8.¹⁵ This gold(II) intermediate is further oxidized by Ru^{III}, giving gold(III)–aryl 9¹⁶ and regenerating the photocatalyst.¹⁷ The proposed gold(III) intermediate 9 accounts for the formation of ligand and diazonium-derived phosphonium salts ([Ph₃P–Ph]⁺ in Scheme 2) after consumption of alkene substrate or in the reaction without alkene (Figure S1).¹⁸ The *anti*-ring expansion of complex 10 furnishes alkylgold(III) intermediate 11, which undergoes a reductive elimination to give the desired product 6 and regenerate the gold(I) catalyst.

Previous gold-catalyzed oxidative functionalization reactions have precluded the use of allenes as substrates because of the

propensity of vinylgold intermediates to undergo facile protodeauration. In contrast, the mechanism outlined in Scheme 2 implies that the gold(III)–aryl is formed directly from the ring expansion event, and therefore reductive elimination might become competitive with protodeauration. In order to further probe this hypothesis and expand the scope of the dual catalysis, the standard reaction conditions were applied to allenes 12a–e (eq 6). These allene substrates were more reactive than alkenes and generally gave moderate yields of the ring-expanded products in shorter time.



In conclusion, we have reported a ring expansion–oxidative arylation reactions of small sized ring-substituted alkenes and allenes. The reaction was promoted by dual visible light photoredox catalysis and gold catalysis at ambient conditions. The mechanism of the reaction was studied by time-resolved FT-IR spectroscopy and is consistent with formal oxidative addition of gold(I) to aryldiazonium salts to form gold(III)–Ar species preceding the reaction with the alkene. These oxidized intermediates react as potent electrophiles toward π -bonds and ultimately provide an entry into formal electrophilic aryl species.

■ ASSOCIATED CONTENT

Supporting Information

Experimental procedures and ¹H NMR spectra. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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Notes

The authors declare no competing financial interest.

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(11) The reaction of **1h** gave 61% yield of **3ha** under the conditions of method D when Ru(bpy)₃(PF₆)₂ was used instead of Ir(ppy)₃.

(12) The reaction shown in Table 1, entry 6, has a slow background reaction in the absence of gold catalyst, which allows for probing the stereochemical course of the phenyl radical-mediated ring expansion. In the absence of gold catalyst, the formation of deuterio-**3fb** was low-yielding and not stereospecific (21% yield, 1:1 dr; see Supporting Information). For radical arylation of styrenes, see ref 10f and Fumagalli, G.; Boyd, S.; Greaney, M. F. *Org. Lett.* **2013**, *15*, 4398.

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(16) The observation of a significant increase in the amount of 4,4'-difluorobiphenyl formation when Ph₃PAuCl was added to 4-FPhN₂BF₄ under photocatalysis conditions in the absence of alkene (Figure S5) is consistent with the generation of a gold(III)–phenyl intermediate.

(17) An alternative mechanism to that shown in Scheme 2, in which **8** reacts with phenyldiazomethane to give **9** and a phenyl radical, without regeneration of the photocatalyst, could not be discounted.

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