DOI: 10.1002/adsc.201600158

Domino Meyer–Schuster/Arylation Reaction of Alkynols or Alkynyl Hydroperoxides with Diazonium Salts Promoted by Visible Light under Dual Gold and Ruthenium Catalysis

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Received: February 5, 2016; Revised: March 2, 2016; Published online: April 27, 2016

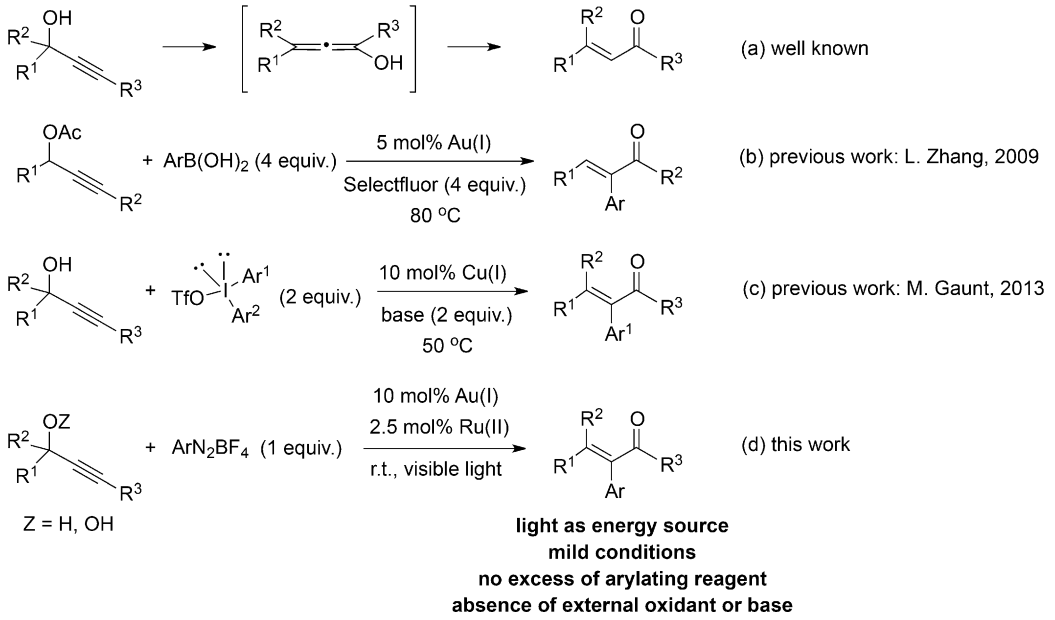
Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/adsc.201600158.

Abstract: A method for the arylative coupling of alkynols or alkynyl hydroperoxides using equimolar amounts of diazonium salts at room temperature has been achieved through application of a gold/photoredox dual catalytic system. The excess of external reagents (oxidant or base) and high temperatures required by previous arylative Meyer–Schuster rearrangement protocols are avoided by exploitation of a visible light-mediated process.

Keywords: alcohols; alkynes; diazo compounds; gold; photocatalysis

In recent years, gold-catalyzed reactions have experienced considerable progress in the field of synthetic organic chemistry.[1] Unfortunately, gold catalysis has not been conveniently exploited in domino functionalization/coupling sequences because of the high redox potential Au(I)/Au(III).[2] Although the inclusion of strong oxidants in the reaction medium has provided access to Au(I)/Au(III) cycles in coupling protocols,[3] the need to add two-fold molar amounts of environmentally unfriendly oxidants [Selectfluor, *N*-fluorobenzenesulfonimide, or (diacetoxyiodo)benzene] is a serious drawback of this strategy. Recently, the seminal works of the groups of Glorius and Toste employed a gold-photoredox co-catalysis that allowed Au(I)/Au(III) catalytic cycles by stepwise one-electron transfers.[4]

On the other hand, the development of efficient synthetic approaches for the α,β-unsaturated ketone structural motif is of great importance because of its presence in a large number of biologically active natural products, as well as its usefulness as precursor for the construction of more complex structures.[5] Traditional procedures for the preparation of enones, such as aldol condensation and olefination reactions present serious limitations. The synthesis of α,β-unsaturated ketones from propargylic alcohols through the Meyer–Schuster rearrangement (Scheme 1a), which consists in a formal 1,3-hydroxy shift followed by tautomerization, represents a tremendous advance in this area.[6] The alkynol rearrangement associated to an extra arylation should provide competitive advantages, because it could afford conjugated enones with internal substitution. However, previous efforts in the arylative Meyer–Schuster rearrangement have been limited to two independent reports, namely, the gold-catalyzed oxidative cross-coupling of propargylic acetates with arylboronic acids (Scheme 1b),[7] and the copper-catalyzed rearrangement of propargylic alcohols using diaryliodonium salts (Scheme 1c).[8] A major shortcoming of both methodologies is the poor atom economy. Moreover, excess of external reagents (oxidant or base) are employed, thus generating additional waste. Furthermore, the use of heat is required in both protocols. With the aim of overcoming theses defects, we suppose that the incorporation of diazonium salts in this sequence could be a great advantage for the area. The arylation step is associated with the concerted elimination of N_2 which preserves our environment because it is free of waste, thus rendering diazonium salts as a green and low-cost source of structural diversity.[9] Besides, a vast array of diverse arenediazonium salts are easily prepared from cheap anilines. Visible light photocatalysis has appeared as a very convenient tool in redox processes.[10] The implementation of the visible light-mediated arylative Meyer–Schuster rearrangement at room temperature

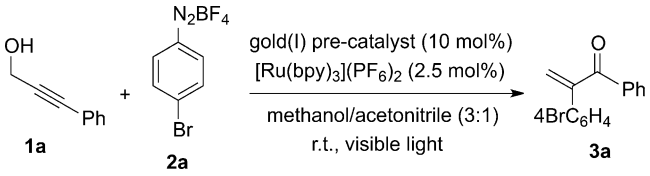


Scheme 1. State of the art for the arylative Meyer–Schuster rearrangement.

is a challenge due to its sustainable aspects. Herein, we disclose the application of diazonium salts as aryl transfer reagents in the gold-photoredox co-catalyzed reaction with alkynols or alkynyl hydroperoxides to the valuable α,β-unsaturated ketone motif (Scheme 1d).[11]

To test the reactivity of the alkynol or alkynyl hydroperoxide moieties, several conditions were screened. Alkynol **1a** and diazonium salt **2a** were chosen as model substrates for the optimization of the reaction parameters. Initially, we tried the arylative Meyer–Schuster rearrangement in the presence of Gagosz' catalyst [$(Ph_3P)AuNTf_2$], and the photoactive ruthenium complex $[Ru(bpy)_3](PF_6)_2$ (bpy = 2,2′-bipyridine), in the presence of visible light (entry 1, Table 1). Fortunately, the proposed reaction between **1a** and **2a** did occur to afford the aryl-substituted α,β-unsaturated ketone **3a** in reasonable yield without traces of the non-arylated α,β-unsaturated ketone counterpart. However, the excess (4 equiv.) of diazonium salt used in previous gold-photoredox processes was not benefitial in our case due to the formation of 1,2-diaryldiazene side products. In an attempt to improve the reaction efficiency, smaller amounts of diazonium salt **2a** were tested in the reaction (entries 2 and 3, Table 1). To our delight, the results showed that the use of equimolecular amounts of diazonium salt **2a** has a dramatic effect on the reaction, sharply improving its cleanliness with the subsequent associated yield increase, under otherwise identical conditions (entry 3, Table 1). A screening of pure and mixed solvents revealed that a mixture methanol/acetonitrile (3:1) was the best reaction medium. A low gold catalyst loading (5 mol%) did not affect the selectivity but

Table 1. Optimization of the reaction conditions for the arylative Meyer–Schuster rearrangement of alkynol **1a** under gold-photoredox co-catalysis.[a]



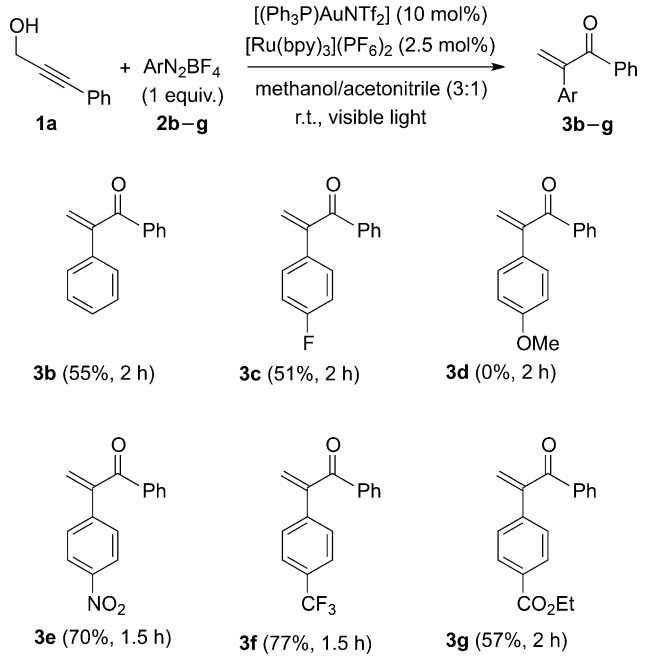
Entry	Gold salt	**2a** (equiv.)	Yield [%][b]
1	$[(Ph_3P)AuNTf_2]$	4	50
2	$[(Ph_3P)AuNTf_2]$	2	62
3	$[(Ph_3P)AuNTf_2]$	1	80
4	$[(Ph_3P)AuNTf_2]$[c]	1	80
5	$[(Ph_3P)AuNTf_2]$[d]	1	68
6	[AuClIPr]	1	5
7	Ph_3PAuCl	1	59
8	$[(Ph_3P)AuNTf_2]$[e]	1	41
9	$[(Ph_3P)AuNTf_2]$[f]	1	34
10	–	1	0
11	$[(Ph_3P)AuNTf_2]$[g]	1	0

[a] Unless otherwise noted, the reaction was carried out using **1a** (1.0 mmol), Au precatalyst (0.01 mmol), $[Ru(bpy)_3](PF_6)_2$ (0.0025 mmol) in MeOH/MeCN (3:1) at room temperature using a fluoresecent light lamp (365 nm) as the light source.
[b] Yield of pure, isolated product **2a** after silica gel chromatography with correct analytical and spectral data.
[c] Au precatalyst (0.02 mmol) was used.
[d] Au precatalyst (0.005 mmol) was used.
[e] $[Ir(ppy)_2(dtbbpy)](PF_6)_2]$ was used.
[f] Fluorescein was used.
[g] The reaction was conducted in the absence of both visible light as well as $[Ru(bpy)_3](PF_6)_2$ catalyst.

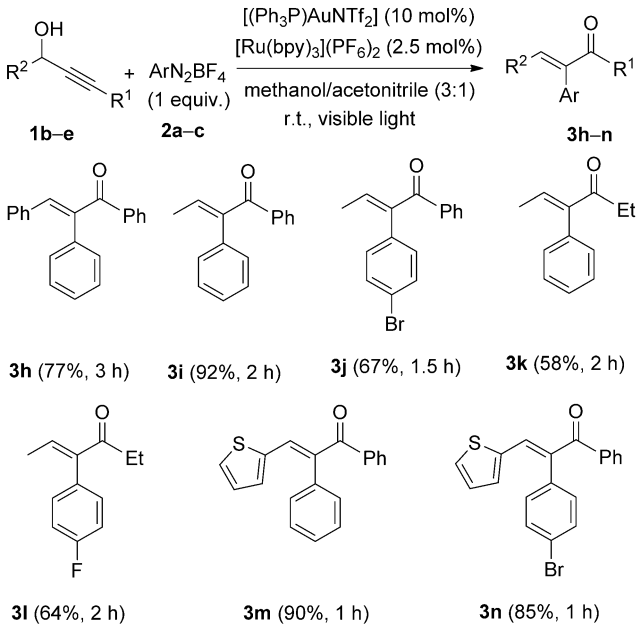
slightly decreased the yield (entry 5, Table 1). Compared with the standard conditions, poor or moderate yields of the product were achieved from the reaction system when [AuClIPr] [IPr = 1,3-bis(2,6-diisopropylphenyl)imidazol-2-ylidene] or Ph_3PAuCl were used to replace $[(Ph_3P)AuNTf_2]$ (entries 6 and 7, Table 1). $[Ru(bpy)_3](PF_6)_2$ was the best photoredox catalyst compared with $[Ir(ppy)_2(dtbbpy)](PF_6)_2$ (ppy = 2-phenylpyridine; dtbbpy = 4,4′-di-*tert*-butyl-2,2′-bipyridine) or fluorescein (entries 8 and 9, Table 1). As anticipated, the gold salt was indispensable for this transformation (entry 10, Table 1). Not unexpectedly, we did not obtain product **3a** while both photoredox catalyst and visible-light were absent in the reaction mixture (stirred in the dark) (entry 11, Table 1).

With the reaction conditions optimized, we then examined the scope of this sequence with respect to the aryldiazonium component. Worthy of note, the challenging primary propargylic alcohol **1a** was prone to react with different arylating partners. As demonstrated in Scheme 2, a series of aryldiazonium salts **2b–g** with substituents on the aryl ring were smoothly converted into the corresponding α-arylated α,β-unsaturated ketones **3b–g** in reasonable yields (up to 77%). It was found that electron-withdrawing substituents normally gave reasonable yields while strongly electron-donating groups (MeO) resulted in failure (**3d**).

In order to explore the generality of this reaction, a wide range of complex alkynols were also tested. The reaction was found not to be significantly affected by the electronic nature of the alkynol substituents.



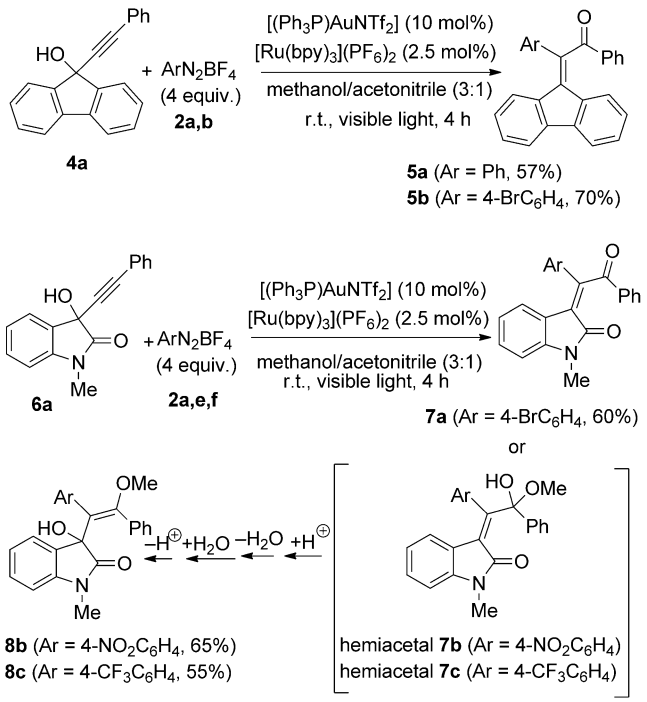
Scheme 2. Synthesis of aryl-substituted α,β-unsaturated ketones **3b–g** through gold-photoredox co-catalyzed arylative Meyer–Schuster rearrangement of primary alkynol **1a**.



Scheme 3. Synthesis of aryl-substituted α,β-unsaturated ketones **3h–n** through gold-photoredox co-catalyzed arylative Meyer–Schuster rearrangement of secondary alkynols **1b–e**.

The reaction worked well with both aliphatic and aromatic substituents, such as in secondary alkynols **1b–e**, giving rise to alkenes **3h–n** with excellent diastereoselectivities (>95:5, *E*/*Z*) (Scheme 3). Gratifyingly, the dialkyl-substituted alkynol **1d** smoothly afforded the corresponding products **3k** and **3l** in fair yields. To further demonstrate the scope of the arylative rearrangement, thiophene derivative **1e** was then applied in the reaction, generating **3m** and **3n** in a competent manner. Clearly, this tandem sequence could be applicable to alkynols bearing a heterocyclic moiety. To show the potential of the methodology, a gram-scale synthesis of **3i** was carried out. It is remarkable that the yield was not decreased when the reaction was scaled-up (1 gram of alkynol **1c**) and the loading of gold catalyst was reduced from 10 mol% to 5 mol%.

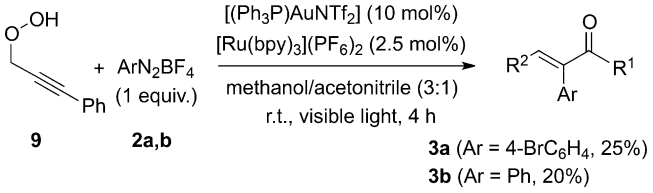
The steric hindrance at the contiguous positions of the alkynol precursors affected the reaction greatly. When 9-ethynyl-9*H*-fluoren-9-ol **4a** was employed, only a trace amount of the desired product **5a** was obtained. The major product (62% yield) was the classical (non-arylative) Meyer–Schuster adduct, which indicates that the bulkiness of the substituents has a negative effect on the arlyation. Gratifyingly, the use of excess of diazonium salt provided aryl-substituted α,β-unsaturated ketones **5a** and **5b** in reasonable yields (57–70%) under otherwise the same reactions conditions (Scheme 4). Compounds **5** can be considered as hybrid scaffolds as a combination of the valuable α,β-unsaturated ketone and fluorene[12] frameworks. It was observed that the arylative Meyer–Schuster rearrangement of heterocycle-containing ter-



Scheme 4. Synthesis of aryl-substituted α,β-unsaturated ketones **5** and **7** through gold-photoredox co-catalyzed arylative Meyer–Schuster rearrangement of tertiary alkynols **4a** and **6a**.

tiary alkynols was equally efficient (Scheme 4). For instance, the relevant[13] 3-acylidene-2-oxindole derivative **7a** could be smoothly afforded in reasonable yield and with total *Z* diastereoselectivity starting from 3-ethynyl-3-hydroxyindolin-2-one **6a** (Scheme 4).[14] Curiously, adducts **7b** and **7c**, initially obtained as their corresponding hemiacetals by 1,2-addition reaction of methanol to the α,β-unsaturated ketone moiety, evolves through protonation, dehydration, and final hydration to oxindole-tethered tetrasubstituted olefins **8b** and **8c**. The stereochemistry of products **8** was unambiguously determined by the NOE analysis of enol ether **8c**. Noticeably, the formation of the arylative Meyer–Schuster rearrangement adducts can be disturbed by some substituent factors (presence of EWG) in the diazonium salt. Notably, Scheme 4 shows how the mild conditions of the gold/photoredox dual catalysis allow the selective formation of functionalized indolin-2-one derivatives without harming the sensitive oxindole ring.

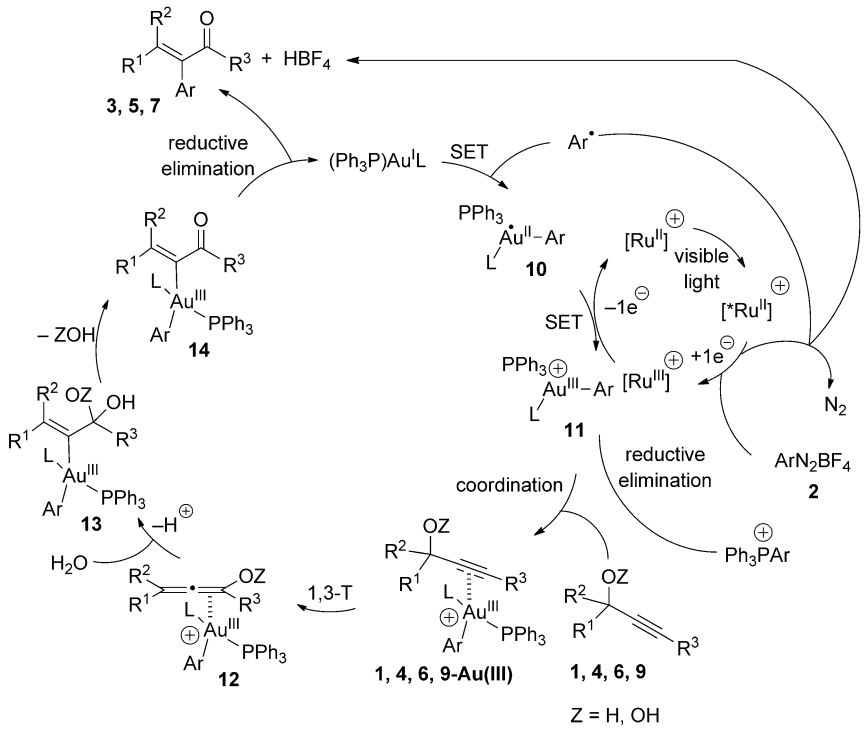
We next turned our attention to the employment of alkynyl hydroperoxides, an under explored kind of substrates in gold catalysis.[15] Indeed, under optimized standard reaction conditions, the arylative rearrangement proceeded. Thus, the reactions of hydroperoxide **9** led to aryl-substituted α,β-unsaturated ketones **3a** and **3b** (Scheme 5), but with diminished yields in comparation to alkynols.



Scheme 5. Synthesis of aryl-substituted α,β-unsaturated ketones **3a** and **3b** through gold-photoredox co-catalyzed arylative Meyer–Schuster rearrangement of alkynyl hydroperoxide **9**.

A plausible mechanism for the gold-photoredox co-catalyzed formation of α,β-unsaturated ketones **3**, **5**, and **7** from alkynols **1**, **4**, and **6** or alkynyl hydroperoxide **9** and diazonium salts **2** is presented in Scheme 6. The cationic organogold(III) intermediate **11**, which may be considered as a robust electrophile, should be formed through photoredox oxidation. Next, arylgold(III) species **11** should interact with the alkynol or alkynyl hydroperoxide moiety with a final aryl group transfer. A catalytic cycle was postulated based on the use of a Ru(II) species as a strong reductant for the generation of an aryl radical from diazonium salts **2**. Initially, Ru(II) complexes are reversibly promoted to their excited state, $[^*Ru(II)]^+$, under visible light exposure. Consecutive transfer of an electron to diazonium salt **2** may generate the corresponding aryl radical, that should be spontaneously paired with the gold(I) salt to form unstable organogold(II) intermediate **10**. Subsequent oxidation by Ru(III) produces arylgold(III) species **11** which, followed by reductive elimination, liberates phosphonium derivative $[Ph_3PAr]^+$,[16] releasing the ruthenium(II) photoredox catalyst into the first catalytic cycle (Scheme 6, right catalytic cycle). Next, alkynols **1**, **4**, and **6** or alkynyl hydroperoxide **9** enter the second catalytic cycle, which is gold-catalyzed, furnishing complex **1**, **4**, **6**, **9**-Au(III) through coordination of the gold salt to the triple bond. Species **1**, **4**, **6**, **9**-Au(III) evolves through a 1,3-hydroxide (hydroperoxide) transposition to intermediate **12**. Regioselective nucleophilic addition of water in gold-allenyl complex **12** to give intermediate **13**, followed by loss of water or hydrogen peroxide, provides the alkenylgold(III) **14**. Reductive elimination linked to proton release liberates α,β-unsaturated ketones **3**, **5**, and **7** with concomitant regeneration of the gold(I) catalyst, closing the second catalytic cycle (Scheme 6, left catalytic cycle).

The mechanism proposed in Scheme 6 is fully consistent with the recent theoretical study of the visible light-mediated gold-catalyzed oxyarylation reaction of alkenes,[17] in which the favorable gold catalytic cycle is the sequence of radical addition, single electron transfer, coordination, cyclization, and reductive elimination.



Scheme 6. Mechanistic explanation for the gold-photoredox co-catalyzed preparation of α,β-unsaturated ketones **3**, **5**, and **7** from alkynols **1**, **4**, and **6** or alkynyl hydroperoxide **9** and diazonium salts **2**.

In conclusion, the direct rearrangement/arylative coupling of alkynols or alkynyl hydroperoxides using equimolar amounts of diazonium salts at room temperature to afford aryl-substituted α,β-unsaturated ketones has been achieved through application of a gold/photoredox dual catalytic system.

Experimental Section

General Methods

^{1}H NMR and ^{13}C NMR spectra were recorded on Bruker AMX-500, Bruker Avance-300, or Varian VRX-300S spectrometers. NMR spectra were recorded in $CDCl_3$ solutions, except where otherwise stated. Chemical shifts are given in ppm relative to TMS (^{1}H, 0.0 ppm), or $CDCl_3$ (^{13}C, 77.0 ppm). Low and high resolution mass spectra were taken on an AGILENT 6520 Accurate-Mass QTOF LC/MS spectrometer using the electrospray mode (ES) unless otherwise stated. IR spectra were recorded on a Bruker Tensor 27 spectrometer. All commercially available compounds were used without further purification.

Typical Procedure for the Arylative Meyer–Schuster Rearrangement of Alkynols or Alkynyl Hydroperoxides using Gold/Photoredox Catalysis

In a flask in the absence of light at −78 °C, [$(Ph_3P)AuNTf_2$] (10 mol%) and [$Ru(bpy)_3$](PF_6)$_2$ (2.5 mol%) were sequentially added to a solution of diazonium salt **2** (1.0 equiv.) and the appropriate alkynol **1** or alkynyl hydroperoxide **9** (1.0 mmol) in a mixture of MeOH/MeCN (3:1, 7.5 mL). The reaction mixture was then warmed to room temperature and stirred under irradiation from visible light source (21 W fluorescent light bulb installed in a tool box). After completion (TLC), diethyl ether was added and the mixture was filtered though a pad of silica gel. The solvent of the filtrate was removed under reduced pressure. Chromatography of the residue using hexanes/ethyl acetate mixtures gave analytically pure compounds. Spectroscopic and analytical data for pure forms of compounds **3**, **5**, **7** and **8** follow.

Aryl-substituted α,β-unsaturated ketone 3a: From 40 mg (0.30 mmol) of alkynol **1a**, and after chromatography of the residue using hexanes/ethyl acetate (4:1) as eluent, gave compound **3a** as a colorless oil; yield: 80 mg (80%). ^{1}H NMR (300 MHz, $CDCl_3$, 25 °C): δ = 7.68 (m, 2H), 7.36 (d, J = 7.3 Hz, 1H), 7.26 (m, 4H), 7.10 (d, J = 8.6 Hz, 2H), 5.89 (s, 1H), 5.48 (s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$, 25 °C): δ = 196.9, 147.0, 136.8, 135.8, 133.2, 131.7 (2C), 129.9 (2C), 128.7 (2C), 128.4 (2C), 122.6, 121.9; IR ($CHCl_3$): ν = 1681, 1589 cm^{-1}; HR-MS (ES): m/z = 287.0079, calcd. for $C_{15}H_{12}BrO$ [M+H]$^+$: 287.0072.

Aryl-substituted α,β-unsaturated ketone 3b: From 26 mg (0.20 mmol) of alkynol **1a**, and after chromatography of the residue using toluene as eluent, gave compound **3b** as a colorless oil yield: 23 mg (55%). ^{1}H NMR (300 MHz, $CDCl_3$, 25 °C): δ = 7.91 (m, 2H), 7.56 (m, 1H), 7.43 (m, 4H), 7.35 (m, 3H), 6.08 (s, 1H), 5.65 (s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$, 25 °C): δ = 197.5, 148.2, 137.0, 136.9, 133.0, 129.9, 128.6 (3C), 128.3 (2C), 127.0 (2C), 120.9 (2C); IR ($CHCl_3$):

ν = 1650, 1597 cm^{-1}; HR-MS (ES): *m/z* = 209.0967, calcd. for $C_{15}H_{13}O$ $[M+H]^+$: 209.0966.

Aryl-substituted α,β-unsaturated ketone 3c: From 40 mg (0.30 mmol) of alkynol **1a**, and after chromatography of the residue using hexanes/ethyl acetate (4:1) as eluent, gave compound **3c** as a colorless oil; yield: 36 mg (51%). ^{1}H NMR (300 MHz, $CDCl_3$, 25 °C): δ = 7.90 (m, 2H), 7.57 (m, 1H), 7.44 (m, 4H), 7.05 (t, *J* = 8.7 Hz, 2H), 6.05 (s, 1H), 5.65 (s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$, 25 °C): δ = 197.3, 162.8 (d, *J* = 248.2 Hz), 147.0, 136.9, 133.1, 129.9 (2C), 128.9, (d, *J* = 8.2 Hz, 2C), 128.4 (2C), 121.3, 115.5 (d, *J* = 21.7 Hz, 2C); IR ($CHCl_3$): ν = 1667, 1509 cm^{-1}; HR-MS (ES): *m/z* = 227.0870, calcd. for $C_{15}H_{12}FO$ $[M+H]^+$: 227.0872.

Aryl-substituted α,β-unsaturated ketone 3e: From 40 mg (0.30 mmol) of alkynol **1a**, and after chromatography of the residue using hexanes/thyl acetate (5:1) as eluent, gave compound **3e** as a colorless oil; yield: 53 mg (70%). ^{1}H NMR (300 MHz, $CDCl_3$, 25 °C): δ = 8.22 (d, *J* = 8.9 Hz, 2H), 7.89 (m, 2H), 7.61 (m, 3H), 7.48 (t, *J* = 7.5 Hz, 2H), 6.27 (s, 1H), 5.89 (s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$, 25 °C): δ = 196.1, 147.6, 146.2, 143.3, 136.6, 133.5, 129.9 (2C), 128.6 (2C), 128.1 (2C), 125.0, 123.8 (2C); IR ($CHCl_3$): ν = 1663, 1515 cm^{-1}; HR-MS (ES): *m/z* = 253.0742, calcd. for $C_{15}H_{11}NO_3$ $[M]^+$: 253.0739.

Aryl-substituted α,β-unsaturated ketone 3f: From 40 mg (0.30 mmol) of alkynol **1a**, and after chromatography of the residue using hexanes/ethyl acetate (5:1) as eluent, gave compound **3f** as a colorless oil; yield: 63 mg (77%). ^{1}H NMR (300 MHz, $CDCl_3$, 25 °C): δ = 7.91 (m, 2H), 7.59 (m, 5H), 7.47 (m, 2H), 6.19 (s, 1H), 5.80 (s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$, 25 °C): δ = 196.7, 146.9, 140.5, 136.8, 133.3, 129.8 (2C), 128.5 (2C), 127.5 (2C), 125.5 (q, *J* = 3.7 Hz, 2C), 123.9 (q, *J* = 272.2 Hz, CF_3), 123.6; IR ($CHCl_3$): ν = 1665, 1325 cm^{-1}; HR-MS (ES): *m/z* = 276.0759, calcd. for $C_{16}H_{11}F_3O$ $[M]^+$: 276.0762.

Aryl-substituted α,β-unsaturated ketone 3g: From 40 mg (0.30 mmol) of alkynol **1a**, and after chromatography of the residue using hexanes/ethyl acetate (7:1) as eluent, gave compound **3g** as a colorless oil; yield: 47 mg (57%). ^{1}H NMR (300 MHz, $CDCl_3$, 25 °C): δ = 8.14 (d, *J* = 8.5 Hz, 1H), 8.02 (m, 2H), 7.89 (m, 2H), 7.69 (d, *J* = 8.5 Hz, 1H), 7.49 (m, 3H), 6.17 (s, 1H), 5.77 (s, 1H), 4.38 (q, *J* = 7.1 Hz, 2H), 1.39 (t, *J* = 7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$, 25 °C): δ = 196.8, 166.1, 147.5, 141.2, 136.8, 133.2, 129.9 (2C), 129.8 (2C), 128.4 (2C), 127.0 (2C), 125.2, 122.8, 61.0, 14.2; IR ($CHCl_3$): ν = 1714, 1684 cm^{-1}; HR-MS (ES): *m/z* = 280.1107, calcd for $C_{18}H_{16}O_3$ $[M]^+$: 280.1099.

Aryl-substituted α,β-unsaturated ketone 3h: From 42 mg (0.20 mmol) of alkynol **1b**, and after chromatography of the residue using toluene as eluent, gave compound **3h** as a colorless solid; yield: 44 mg (77%); mp 99–101 °C. ^{1}H NMR (300 MHz, $CDCl_3$, 25 °C): δ = 7.89 (m, 2H), 7.50 (m, 3H), 7.29 (m, 9H), 7.12 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$, 25 °C): δ = 197.6, 140.7, 140.1, 138.1, 136.4, 134.7, 132.1, 130.3 (2C), 129.7 (2C), 129.6 (2C), 128.9, 128.7 (2C), 128.2 (2C), 128.1 (2C), 127.9; IR ($CHCl_3$): ν = 1652, 1266 cm^{-1}; HR-MS (ES): *m/z* = 285.1275, calcd. for $C_{21}H_{17}O$ $[M+H]^+$: 285.1279.

Aryl-substituted α,β-unsaturated ketone 3i: From 29 mg (0.20 mmol) of alkynol **1c**, and after chromatography of the residue using toluene as eluent, gave compound **3i** as a colorless oil; yield: (40 mg (92%). ^{1}H NMR (300 MHz, $CDCl_3$, 25 °C): δ = 7.78 (d, *J* = 7.0 Hz, 1H), 7.38 (m, 8H), 6.61 (q, *J* = 7.1 Hz, 1H), 1.90 (d, *J* = 7.1 Hz, 2H); ^{13}C NMR (75 MHz, $CDCl_3$, 25 °C): δ = 197.2, 142.7, 139.7, 138.3, 135.7, 131.8, 129.5 (4C), 128.2 (2C), 128.0 (2C), 127.4, 15.5; IR ($CHCl_3$): ν = 1730, 1684, 1091 cm^{-1}; HR-MS (ES): *m/z* = 223.1117, calcd. for $C_{16}H_{15}O$ $[M+H]^+$: 223.1123.

Aryl-substituted α,β-unsaturated ketone 3j: From 29 mg (0.20 mmol) of alkynol **1c**, and after chromatography of the residue using toluene as eluent, gave compound **3j** as a colorless oil; yield: 41 mg (67%). ^{1}H NMR (300 MHz, $CDCl_3$, 25 °C): δ = 7.74 (m, 2H), 7.52 (m, 2H), 7.43 (m, 3H), 7.15 (d, *J* = 8.4 Hz, 2H), 6.63 (q, *J* = 7.1 Hz, 1H), 1.87 (d, *J* = 7.1 Hz, 2H); ^{13}C NMR (75 MHz, $CDCl_3$, 25 °C): δ = 196.7, 141.7, 140.6, 138.1, 134.6, 131.9, 131.4 (2C), 131.3 (2C), 129.5 (2C), 128.2 (2C), 121.6, 15.6; IR ($CHCl_3$): ν = 1658, 1269 cm^{-1}; HR-MS (ES): *m/z* = 301.0228, calcd. for $C_{16}H_{14}BrO$ $[M+H]^+$: 301.0228.

Aryl-substituted α,β-unsaturated ketone 3k: From 19 mg (0.20 mmol) of alkynol **1d**, and after chromatography of the residue using toluene as eluent, gave compound **3k** as a colorless oil; yield: 20 mg (58%). ^{1}H NMR (300 MHz, $CDCl_3$, 25 °C): δ = 7.36 (m, 3H), 7.11 (d, *J* = 8.0, 1.5 Hz, 2H), 6.99 (q, *J* = 7.1 Hz, 1H), 2.55 (q, *J* = 7.3 Hz, 1H), 1.71 (d, *J* = 7.1 Hz, 1H), 1.06 (t, *J* = 7.3 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$, 25 °C): δ = 201.4, 143.5, 137.4, 136.1, 129.6 (2C), 128.2 (2C), 127.3, 32.8, 15.4, 8.3; IR ($CHCl_3$): ν = 1681, 1625 cm^{-1}; HR-MS (ES): *m/z* = 175.1123, calcd. for $C_{12}H_{15}O$ $[M+H]^+$: 175.1123.

Aryl-substituted α,β-unsaturated ketone 3l: From 19 mg (0.20 mmol) of alkynol **1d**, and after chromatography of the residue using hexanes/ethyl acetate (20:1) as eluent, gave compound **3l** as a colorless oil; yield: 28 mg (64%). ^{1}H NMR (300 MHz, $CDCl_3$, 25 °C): δ = 7.07 (m, 4H), 7.00 (q, *J* = 7.1 Hz, 1H), 2.59 (q, *J* = 7.3 Hz, 2H), 1.72 (d, *J* = 7.1 Hz, 3H), 1.07 (t, *J* = 7.3 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$, 25 °C): δ = 201.1, 162.1 (d, *J* = 246.2 Hz), 142.7, 138.2, 131.7, (d, *J* = 3.4 Hz), 131.3, (d, *J* = 8.0 Hz, 2C), 115.2 (d, *J* = 8.0 Hz, 2C), 32.4, 15.5, 8.4; IR ($CHCl_3$): ν = 1679, 1511 cm^{-1}; HR-MS (ES): *m/z* = 193.1015, calcd. for $C_{12}H_{14}FO$ $[M+H]^+$: 193.1029.

Aryl-substituted α,β-unsaturated ketone 3m: From 43 mg (0.20 mmol) of alkynol **1e**, and after chromatography of the residue using toluene as eluent, gave compound **3m** as a colorless oil; yield: 53 mg (90%). ^{1}H NMR (300 MHz, $CDCl_3$, 25 °C): δ = 7.82 (m, 1H), 7.50 (m, 7H), 7.37 (m, 2H), 7.27 (m, 1H), 7.09 (m, 1H), 6.94 (dd, *J* = 5.1, 3.7 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$, 25 °C): δ = 196.4, 138.5 (2C), 137.7, 135.8, 135.5, 133.3, 131.6, 130.7, 129.9 (2C), 129.3 (2C), 129.1 (2C), 128.4, 128.2 (2C), 126.7; IR ($CHCl_3$): ν = 1641, 1600 cm^{-1}; HR-MS (ES): *m/z* = 291.0842, calcd. for $C_{19}H_{15}OS$ $[M+H]^+$: 291.0844.

Aryl-substituted α,β-unsaturated ketone 3n: From 43 mg (0.20 mmol) of alkynol **1e**, and after chromatography of the residue using hexanes/ethyl acetate (10:1) as eluent, gave compound **3n** as a colorless oil; yields: 63 mg (85%). ^{1}H NMR (300 MHz, $CDCl_3$, 25 °C): δ = 7.70 (m, 2H), 7.54 (d, *J* = 8.4 Hz, 2H), 7.47 (m, 2H), 7.39(m, 2H), 7.23 (d, *J* = 5.0 Hz, 1H), 7.15 (d, *J* = 8.4 Hz, 2H), 7.02 (m, 1H), 6.88 (dd, *J* = 5.1, 3.7 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$, 25 °C): δ = 196.1, 138.3, 138.1, 136.4, 136.0, 134.7, 133.7, 132.4 (2C), 131.8 (2C), 131.7, 131.0, 129.3 (2C), 128.3 (2C), 126.9,

122.9; IR ($CHCl_3$): ν = 1643, 1601 cm^{-1}; HR-MS (ES): *m/z* = 367.9872, calcd. for $C_{19}H_{13}BrOS$ $[M]^+$: 367.9870.

Aryl-substituted α,β-unsaturated ketone 5a: From 56 mg (0.20 mmol) of alkynol **4a**, and after chromatography of the residue using toluene as eluent, gave compound **5a** as a yellow solid; yield: 41 mg (57%); mp 174–176 °C. ^1H NMR (300 MHz, $CDCl_3$, 25 °C): δ = 8.19 (d, *J* = 7.5 Hz, 2H), 7.70 (d, *J* = 7.4 Hz, 2H), 7.57 (m, 3H), 7.46 (m, 5H), 7.31 (m, 3H), 7.04 (d, *J* = 8.0 Hz, 1H), 6.97 (t, *J* = 8.0 Hz, 1H), 6.72 (d, *J* = 7.9 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$, 25 °C): δ = 197.4, 140.9, 140.5, 140.4, 137.0, 136.3, 136.0, 135.1, 134.7, 134.0, 130.0 (2C), 129.2 (2C), 129.0 (4C), 128.8, 128.7, 128.6, 127.1, 126.8, 125.3, 124.8, 119.5, 119.4; IR ($CHCl_3$): ν = 1646, 1596 cm^{-1}; HR-MS (ES): *m/z* = 358.1352, calcd. for $C_{27}H_{18}O$ $[M]^+$: 358.1358.

Aryl-substituted α,β-unsaturated ketone 5b: From 56 mg (0.20 mmol) of alkynol **4a**, and after chromatography of the residue using toluene as eluent, gave compound **5b** as a yellow solid; yield: 61 mg (70%); mp 198–200 °C. ^1H NMR (300 MHz, $CDCl_3$, 25 °C): δ = 8.04 (m, 2H), 7.60 (dd, *J* = 7.5, 3.4 Hz, 2H), 7.49 (m, 3H), 7.37 (m, 4H), 7.21 (m, 3H), 6.92 (t, *J* = 7.6 Hz, 2H), 6.70 (d, *J* = 7.9 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$, 25 °C): δ = 197.0, 141.1, 140.6, 138.9, 136.7, 136.2, 135.2, 135.0, 134.9, 134.2, 132.5 (2C), 130.8 (2C), 130.0 (2C), 129.1 (2C), 129.0, 128.8, 127.2, 126.9, 125.2, 124.9, 123.1, 119.7, 119.6; IR ($CHCl_3$): ν = 1644, 1595 cm^{-1}; HR-MS (ES): *m/z* = 436.0451, calcd. for $C_{27}H_{17}BrO$ $[M]^+$: 436.0463.

Aryl-substituted α,β-unsaturated ketone 7a: From 53 mg (0.20 mmol) of alkynol **6a**, and after chromatography of the residue using hexanes/ethyl acetate (3:1) as eluent, gave compound **7a** as a yellow solid; yield: 50 mg (60%); mp 213–215 °C; ^1H NMR (300 MHz, $CDCl_3$, 25 °C): δ = 8.03 (m, 2H), 7.54 (m, 7H), 7.30 (m, 1H), 7.02 (d, *J* = 7.6 Hz, 1H), 6.85 (m, 2H), 3.17 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$, 25 °C): δ = 195.7, 166.2, 147.5, 144.9 (2C), 135.1, 133.0, 132.5 (2C), 130.5, 129.8 (2C), 128.9 (2C), 128.8 (2C), 126.5, 124.2, 123.2, 122.0, 120.2, 108.4, 25.9; IR ($CHCl_3$): ν = 1708, 1668, 1606 cm^{-1}; HR-MS (ES): *m/z* = 417.0361, calcd. for $C_{23}H_{16}BrNO$ $[M]^+$: 417.0364.

Oxindole-tethered tetrasubstituted olefin 8b: From 53 mg (0.20 mmol) of alkynol **6a**, and after chromatography of the residue using hexanes/ethyl acetate (3:1) as eluent, gave compound **8b** as a yellow solid; yield: 54 mg (65%); mp 95–97 °C; ^1H NMR (300 MHz, $CDCl_3$, 25 °C): δ = 7.96 (d, *J* = 8.7 Hz, 2H), 7.28 (m, 4H), 7.14 (m, 3H), 7.03 (m, 3H), 6.85 (d, *J* = 7.8 Hz, 1H), 4.08 (s, 1H), 3.24 (s, 3H), 3.13 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$, 25 °C): δ = 177.0, 155.7, 146.4, 143.6, 143.5, 133.1 (2C), 132.5, 131.2, 130.0 (2C), 129.6, 128.8, 128.0 (2C), 123.7, 122.9, 122.5 (2C), 122.4, 108.3, 77.0, 57.0, 26.3; IR ($CHCl_3$): ν = 3358, 1706, 1608, cm^{-1}; HR-MS (ES): *m/z* = 416.1368, calcd. for $C_{24}H_{20}N_2O_5$ $[M]^+$: 416.1372.

Oxindole-tethered tetrasubstituted olefin 8c: From 53 mg (0.20 mmol) of alkynol **6a**, and after chromatography of the residue using hexanes/ethyl acetate (3:1) as eluent, gave compound **8c** as a yellow solid; yield: 48 mg (55%); mp 195–197 °C. ^1H NMR (300 MHz, $CDCl_3$, 25 °C): δ = 7.33 (m, 6H), 7.08 (m, 6H), 6.84 (d, *J* = 7.7 Hz, 1H), 3.26 (s, 1H), 3.25 (s, 3H), 3.12 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$, 25 °C): δ = 177.1, 155.1, 143.8, 139.8, 132.7, 132.5 (2C), 131.5, 129.9 (2C), 129.5, 128.8 (q, *J* = 32.4 Hz), 128.4, 127.9 (2C), 124.3 (q, *J* = 3.7 Hz, 2C), 124.0 (q, *J* = 272.3 Hz, CF_3), 123.8, 122.9, 122.8, 108.2, 77.0, 57.0, 26.2; IR ($CHCl_3$): ν = 3357, 1704, 1605 , cm^{-1}; HR-MS (ES): *m/z* = 439.1389, calcd. for $C_{25}H_{20}F_3NO_3$ $[M]^+$: 439.1395.

Acknowledgements

Support for this work by MINECO and FEDER (Projects CTQ2012-33664-C02-01, CTQ2012-33664-C02-02, CTQ2015-65060-C2-1-P, and CTQ2015-65060-C2-2-P) is gratefully acknowledged. E. B. thanks MINECO for a postdoctoral contract.

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