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[(NHC)AuCl]-catalyzed Meyer–Schuster rearrangement: scope and limitations

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ABSTRACT

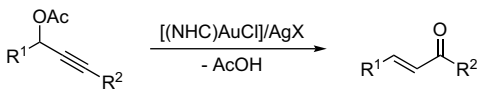
An efficient catalytic system allowing for the synthesis of a variety of α,β-unsaturated ketones has been developed. [(NHC)AuCl] (NHC=N-heterocyclic carbene) in the presence of a silver(I) salt was found to catalyze the Meyer–Schuster rearrangement, leading to α,β-unsaturated ketones from easily accessible propargylic alcohols in high yields. Catalysis was performed in a 2:1 mixture of methanol and water at 60 °C and afforded good yields even for tertiary alcohols and sterically demanding substrates. Thorough evaluation of the present catalytic system uncovered that it was unsuitable for terminal alkynes and primary alcohols. In these cases low yields of the target molecules were obtained due to the formation of unexpected by-products.

1. Introduction

The interest for α,β-unsaturated carbonyl compounds is linked to their general importance in synthesis. Such compounds are useful building blocks, e.g., in total synthesis of natural products,[1] display biological activities[2] and are notably used as substrates in cyclopropanation,[3] Michael-additions[4] and cycloadditions such as the Diels–Alder reaction.[5] Hence, efficient procedures leading to these substrates are of interest. Typical approaches to α,β-unsaturated ketones are the aldol condensation,[6] including the Knoevenagel reaction,[7] and the Horner–Wadsworth–Emmons (HWE) reaction which produces unsaturated esters.[8] These classical reactions have proved to be very useful and are well established as standard procedures. Nevertheless, for synthetic chemists there is still an interest in developing new routes to unsaturated carbonyl compounds as in some cases standard procedures fail to provide expected results. Furthermore, some of these methods generate considerable amount of waste and do not meet the standards of modern and environmentally friendly chemistry. In this context, the isomerization of propargylic alcohols into α,β-unsaturated ketones and aldehydes allows total atom economy[9] and represents an attractive alternative. As the Rupe[10] and the Meyer–Schuster rearrangement,[11] this transformation can be catalyzed by several transition metals.[12]

Recently, gold has shown to be useful in catalysis. The activation of alkynes by $Au^{I,III}$ leading to a manifold of new structures and reactivity highlights the use of gold as an excellent activator of π-systems.[13] The Lewis acidity of gold complexes and their ability to activate alkynes as well as allenes for inter- or intramolecular nucleophilic attack has prompted intensive research, notably involving oxo-nucleophiles.

Gold-catalyzed formation of α,β-unsaturated enones can be performed using readily accessible propargylic acetates as substrates.[14] Zhang et al. recently reported the formation of unsaturated ketones catalyzed by $[(PPh_3)AuNTf_2]$.[15] Concomitantly, our group reported the $[(NHC)Au^{I}]$-catalyzed formation of enones as well as enals from propargylic acetates (Scheme 1).[16] Computational studies on the mechanism of this reaction led us to propose the unexpected activation of water by gold(I) instead of activation of the π-system. Formation of conjugated enones from propargylic alcohols in the presence of gold is also known. The Au^{III}-catalyzed rearrangement of propargylic alcohols was notably observed by Campagne et al., when using 5 mol % of $NaAuCl_4$ as catalyst in the presence of ethanol.[17] Dudley reported the preparation of α,β-unsaturated esters, aiming to find an alternative methodology to the HWE olefination of hindered ketones by using electron-rich



Scheme 1. Formation of α,β-unsaturated enones from propargylic acetates.

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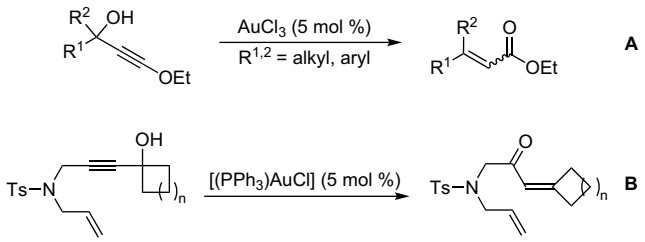


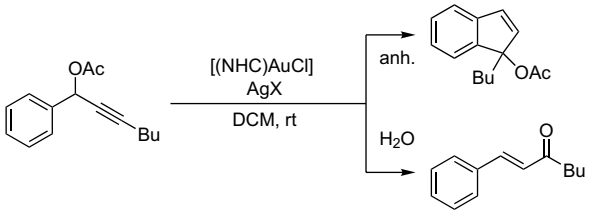
Scheme 2. Meyer–Schuster rearrangements reported by Dudley and Chung.

ethoxyacetylene and tertiary propargylic alcohols (Scheme 2, A). While a tertiary alcohol should facilitate the proposed ionization of the C–O bond, the use of electron-rich alkynes enforces alkyne activation by a soft Lewis-acid catalyst such as $AuCl_3$.[18] An advantage of activating the alkyne instead of the alcohol function is the elimination of the concurring Rupe rearrangement.[10] Dudley et al. later reported an improved catalytic system with expanded scope using Au^{I} instead of Au^{III}.[19] Au^{I}-catalyzed Meyer–Schuster rearrangement of propargylic alcohols was also reported by Chung et al. in 2007 using [(PPh_3)AuCl] (Scheme 2, B),[20] but only moderate to good yields were obtained for specific substrates. Recently, Akai et al. disclosed a promising catalytic system applicable to primary alcohols but requiring [$MoO_2(acac)_2$] in addition to [(PPh_3)AuCl] and AgOTf.[21]

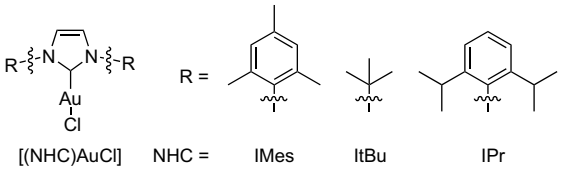
In this contribution, we present a general procedure to produce α,β-unsaturated ketones and esters in good yields and high stereocontrol with a [(NHC)AuCl]-catalyst under mild reaction conditions. The scope and a proposed mechanism will be discussed as well as the limitations of the present catalytic system.

2. Results and discussion

As gold behaves as an excellent catalyst for π-activation, our aim is to explore the scope of gold–NHC complexes in catalysis.[22] Amongst others, we reported in this context the formation of indenes using propargylic acetates as substrates under anhydrous conditions[23] as well as the formation of enones in the presence of water (Scheme 3).[16] Our interest in propargylic alcohols lies in the fact that they are readily available, presenting a more straightforward synthesis, usually in one step from addition of an acetylide onto a ketone or an aldehyde. As a starting point, we used compound **1a** with 2 mol % of [(IPr)AuCl] in the presence of $AgSbF_6$ in DCM. While there was no conversion under anhydrous conditions, we observed the formation of remarkable amounts of the Meyer–Schuster product **2a** when using technical grade DCM. After testing a broad spectrum of solvents, we decided to use MeOH for further reactions. We made a brief screening of commonly used gold–NHC complexes (Scheme 4). Noteworthy, [(IPr)AuCl] was found to be by far the best catalyst in comparison to [(IMes)AuCl] and [(ItBu)AuCl] (Table 1, entries 1–6). [(IPr)AuCl] and silver tetrafluoroborate were independently tested as catalyst, in both cases the starting material was recovered unchanged (entries 7 and 8). Concerning the nature of the silver salts, $AgBF_4$ gave similar results compared to $AgSbF_6$.



Scheme 3. [(NHC)AuCl]-catalyzed formation of indenes and enones.



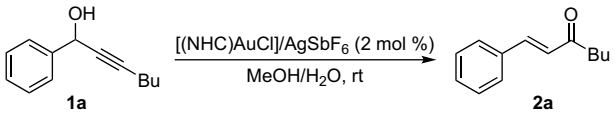
Scheme 4. Gold–NHC complexes used.

Lowering the catalyst loading from 2 mol % to 0.1 mol % only led to minor conversion despite prolonged reaction time.

Having an efficient catalytic system in hand, we explored the scope of this transformation. It should be noted that the reaction time and the temperature necessary to reach full conversion were found highly dependent of the substrates. So, in order to ensure complete conversion of all substrates, reactions were heated overnight. To examine the influence of substituents on the aryl moiety, different aryl derivatives with a butyl chain in the acetylenic position were first screened. As illustrated in Table 2, good to excellent yields were obtained for a variety of substrates. Substitution of the aromatic ring with electron-withdrawing groups (entries 2 and 3) furnished slightly lower yields compared to **1a**. On the other hand, electron-donating substituents (entries 4 and 5) as well as the tertiary alcohol **1f** (entry 6) afforded excellent results. Of note, **1a**–**1e** were selectively converted into the (*E*)-isomers. This result is in line with the stereoselective conversion of propargylic acetates we previously reported.[16] Furthermore, the present catalytic system equals or outperforms other catalytic systems for the Meyer–Schuster rearrangement of propargylic alcohols.[18–21]

Next, the effect of the acetylenic substituent was examined while keeping an unsubstituted phenyl ring at the propargylic position (Table 3). When the acetylenic substituent was modified from *n*-butyl to *tert*-butyl, a good conversion into the corresponding product was observed (entry 1). This is remarkable since the corresponding propargylic acetate failed to react with our previous catalytic system.[16] Using activating substituents such as a phenyl group (entry 2) provided excellent conversion. Interestingly, with **1i**, transesterified methoxyester $\mathbf{2i_a}$ was obtained quantitatively when using MeOH as solvent (entry 3). In order to avoid this transesterification, the same reaction was performed in dioxane. With a yield of up to 97%, an *E*/*Z* ratio of 5:1 was observed. This represents a slightly better stereoselectivity for compound $\mathbf{2i_b}$ than reported previously by Dudley et al.[12i] Changing from ethoxy alkyne **1i** to ethoxy propiolate **1j**, reactivity was clearly switched, leading to the unexpected product **2j** in 69% yield (entry 5).

Table 1
Catalyst screening for Meyer–Schuster rearrangement[a]

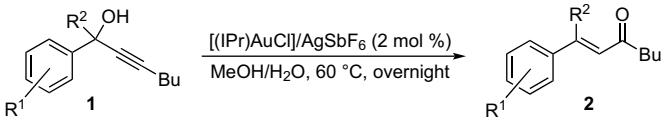


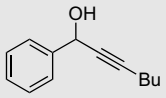
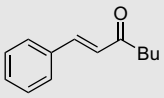
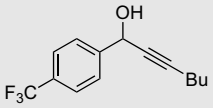
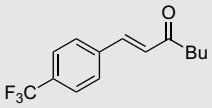
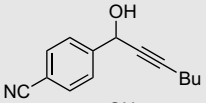
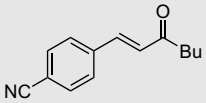
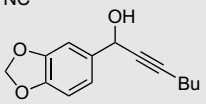
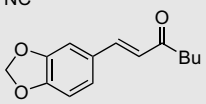
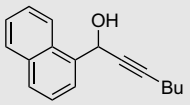
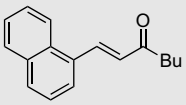
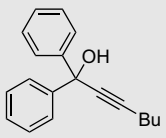
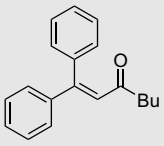
1a 2a

Entry	Catalyst	Time	Conv.[b] (%)
1	[(IPr)AuCl]	70 min	80
2	[(IMes)AuCl]	70 min	27
3	[(ItBu)AuCl]	70 min	37
4	[(IPr)AuCl]	4 h	99
5	[(IMes)AuCl]	4 h	42
6	[(ItBu)AuCl]	4 h	70
7	Only $AgSbF_6$	3 h	0
8	Only [(IPr)AuCl]	3 h	0

[a] Reaction conditions: **1a** (0.27 mmol) in MeOH (2 mL), water (0.3 mL), [(NHC)AuCl]/$AgSbF_6$(2 mol %), rt.
[b] Conversion determined by GC.

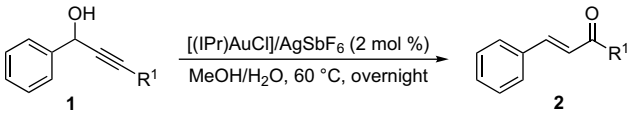
Table 2
Effect of aryl derivatives in propargylic position

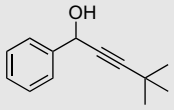
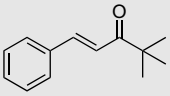
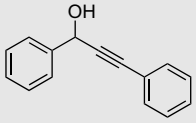
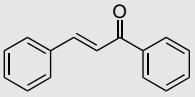
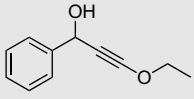
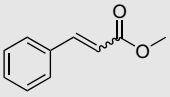
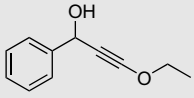
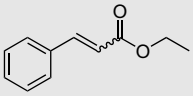
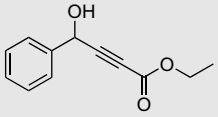
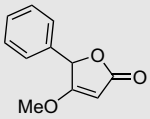


Entry	Propargylic alcohol	1	Enone	2	Yield[a] (%)
1		**1a**		**2a**	96
2		**1b**		**2b**	81[b]
3		**1c**		**2c**	74[b]
4		**1d**		**2d**	81[b]
5		**1e**		**2e**	92[b]
6		**1f**		**2f**	96

[a] NMR yields with respect to benzaldehyde as internal standard are average of two runs.
[b] Isolated yield.

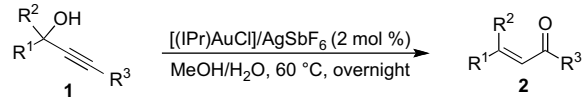
Table 3
Effect of acetylenic substituents

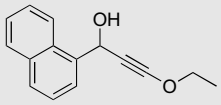
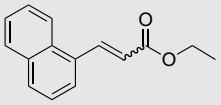
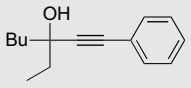
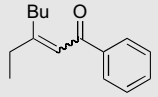
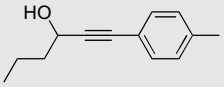
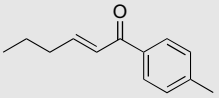
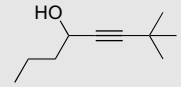
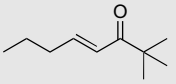
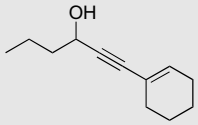
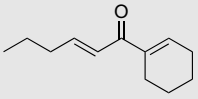
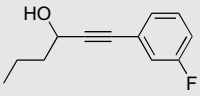
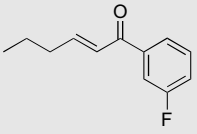


Entry	Propargylic alcohol	1	Enone	2	Yield[a] (%)
1		**1g**		**2g**	86
2		**1h**		**2h**	95
3		**1i**		**2i$_a$**	81 *E*/*Z* 1.5:1
4[b]		**1i**		**2i$_b$**	71 *E*/*Z* 5:1
5		**1j**		**2j**	69[c]

[a] NMR yields with respect to benzaldehyde as internal standard are average of two runs.
[b] Reaction performed in dioxane to avoid transesterification.
[c] Isolated yield.

Table 4
Screening of substrates with varied substitution patterns



Entry	Propargylic alcohol	1	Enone	2	Yield[a] (%)
1[b]		**1k**		**2k**	86 *E*/*Z* 5:1
2		**1l**		**2l**	86 *E*/*Z* 1:1
3		**1m**		**2m**	96
4		**1n**		**2n**	28
5		**1o**		**2o**	58
6		**1p**		**2p**	89[c]

[a] NMR yields with respect to benzaldehyde as internal standard are average of two runs.
[b] Reaction performed in dioxane to avoid transesterification.
[c] Isolated yield.

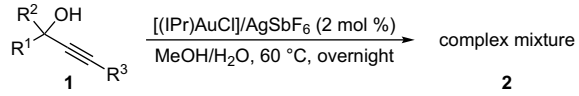
Remarkably, when using 1,4-dioxane as solvent neither the Meyer–Schuster rearrangement nor the formation of a lactone was observed. Instead, the hydration of the alkyne leading to the corresponding α-hydroxy ketone was obtained.

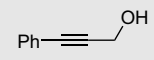
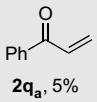
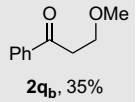
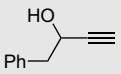
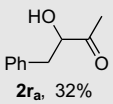
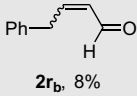
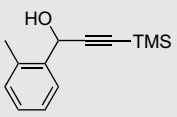
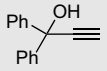
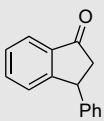
Finally, Table 4 shows an extended scope of the reaction. As with the results in Table 3, when using the ethoxy alkyne **1k** good yields and stereoselectivity (Table 4, entry 1) were achieved. Entries 4 and 5 illustrate poor to moderate yields. Obviously, the absence of an aryl substituent decreases the conversion of propargylic alcohols into the corresponding enones. Entries 3 and 6 present examples for 'switched' substitution compared to Tables 2 and 3. Conversion of substrates having the aryl moiety in the acetylenic position while there is an alkyl substituent in a propargylic position, was comparable to results for other substrates. The conversion of the tertiary propargylic alcohol **1l** (entry 2), gave as expected a 1:1 mixture of the two diastereomers of **2l** as the butyl and the ethyl chain can hardly be differentiated structurally.

As shown in Tables 2–4, [(IPr)AuCl] in the presence of $AgSbF_6$ represents an adequate and fairly stereoselective catalytic system for the substrates tested so far. Except for compound **1j** (Table 3, entry 5) showing a different but interesting reactivity.

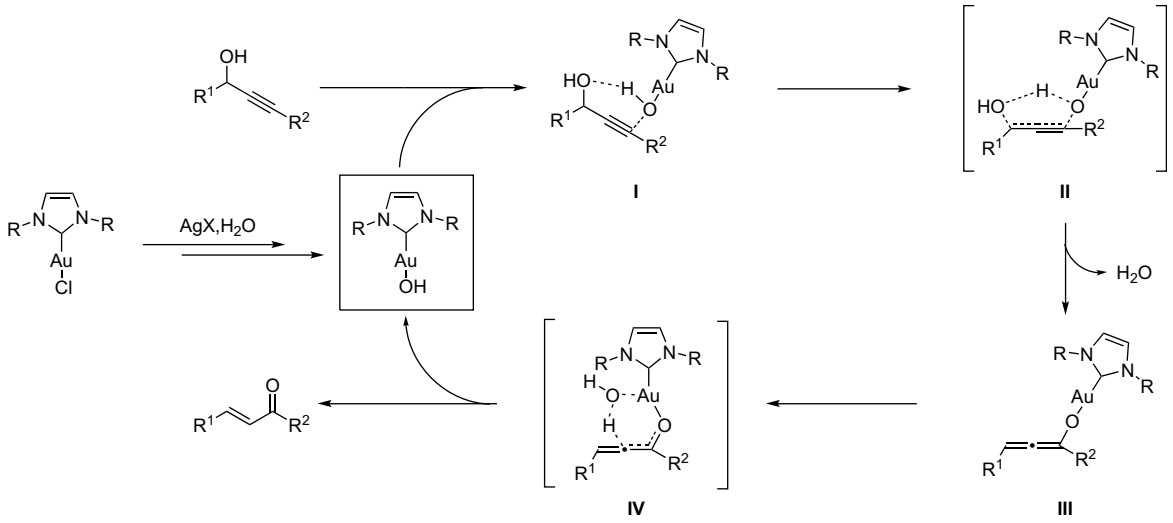
In spite of the remarkable scope of this catalytic system it is limited to substrates substituted in the acetylenic and propargylic positions. Experiments using either primary alcohols or terminal alkynes gave complex product mixtures. More specifically, the formation of the enone or enal was always observed, but yields were minor due to the important formation of by-products. Similar results were achieved when using alkynes with a trimethylsilyl group (TMS) in the acetylenic position (Table 5, entry 3). A compilation of substrates not suitable, under these conditions, for the Meyer–Schuster rearrangement is presented in Table 5. Compound **1r** showed low reactivity towards the Meyer–Schuster rearrangement and Au^I-catalyzed hydration of the triple bond was observed instead.[24] Finally, we would like to point out the formation of 3-

Table 5
Substrates exhibiting low reactivity[a]



Entry	Propargylic alcohol	1	Product, yield (%)	
1[b]		**1q**	 **$2q_a$**, 5%	 **$2q_b$**, 35%
2		**1r**	 **$2r_a$**, 32%	 **$2r_b$**, 8%
3		**1s**	Complex mixture	
4		**1t**	 **2t**, 9%	

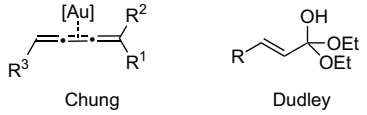
[a] NMR yields with respect to benzaldehyde as internal standard are average of two runs.
[b] Reaction performed at room temperature.



Scheme 5. Proposed mechanism for the [(NHC)AuCl] catalyzed Meyer–Schuster rearrangement.

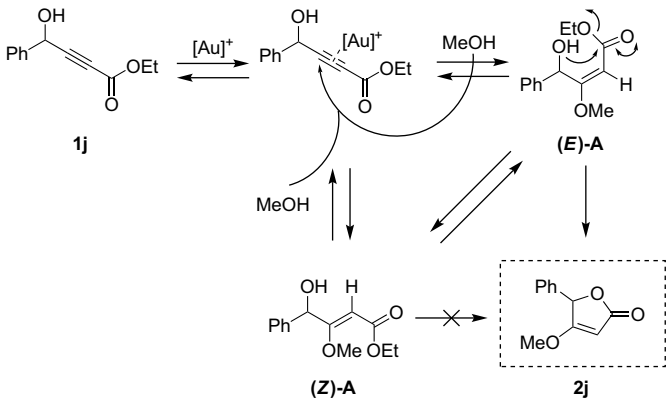
phenyl-indanone from alkynol **1t**, isolated with a poor yield of 9%. In the literature, the conversion of a propargylic alcohol into an indanone derivative has been achieved by rhodium-catalyzed isomerization,[25] whereas no Au^I-catalyzed process has been reported so far to the best of our knowledge. We propose a mechanism with the initial conversion of the propargylic alcohol into the enal, followed by a Au^I-activation of either the aryl or more likely the aldehyde moiety leading to an allyl alcohol that can isomerize into **2t**.[26] Since both types of activation are unusual for gold(I) complexes, investigations on this reactivity are being pursued.

For the Meyer–Schuster rearrangement, Dudley postulated a mechanism catalyzed by gold(I) as well as a revised one for scandium(III).[12i] Even if the mechanism was supported by experimental results, we suppose, due to noteworthy differences between both systems, that a different reaction pathway is involved. Dudley postulated the initial attack of the solvent, ethanol, followed by the attack of a water molecule to form an intermediate, shown in Scheme 6, that can convert into the conjugated ester. Using methanol instead of ethanol lead to a 1:1 mixture of unsaturated ethoxy and methoxyester, supporting their mechanistic proposal. In contrast to Dudley, we observed with **1i** (Table 3, entry 3) as well as with **1k** (Table 4, entry 1) quantitative transesterification to unsaturated methoxyester when using MeOH as solvent. Noteworthy, $\mathbf{2i_b}$ was recovered when subjected to standard reaction conditions in MeOH. This excludes the possibility of a Meyer–Schuster rearrangement followed by a gold-catalyzed transesterification and suggests another reaction pathway. On the other hand, $\mathbf{2i_b}$ (Table 3, entry 4) and **2k** (Table 4, entry 1) were formed in high yields in 1,4-dioxane as solvent. Chung et al. proposed another mechanism, which involves a cumulene intermediate (Scheme 6).[20] As all compounds presented in Table 4 do not bear the proton needed in the propargylic position to form such a cumulene intermediate, we can exclude such a reaction pathway. Hence, we propose the mechanism shown in Scheme 5. Instead of activating the triple bond, we propose that the catalyst could 'activate' a molecule of water to form a gold–hydroxo complex as we previously postulated based on DFT calculations.[16] This [(NHC)AuOH] species could then attack the triple bond to give **I**. Transition state **II** should facilitate elimination of water leading to the activated allenolate **III**. The gold–hydroxo complex could finally be regenerated through interaction with another water molecule with release of the reaction product as illustrated in **IV**. Nevertheless, a straightforward mechanism with the triple bond activated by gold involving a water attack to form an allenol that tautomerizes into the product cannot be excluded at this time.



Scheme 6. Key intermediates in the proposed mechanisms by Chung and Dudley.

Regarding the formation of furanone **2j** we suggest a different pathway in which MeOH attacks the gold-activated triple bond leading to a vinylether **A**. If the (*E*)-isomer is formed, the hydroxy group is spacially close enough to attack the ester leading to the furanone derivative (Scheme 7). In the case of the formation of the



Scheme 7. Proposed mechanism for the conversion of **1j** into **2j.**

(*Z*)-isomer we suggest that under the reaction conditions the (*Z*)-isomer could isomerize into the (*E*)-isomer. At this time we are investigating the reactivity of α-hydroxy propiolates with [(NHC)AuCl] in order to obtain further mechanistic insights.

3. Conclusion

We have presented an NHC–gold(I) based catalytic system enabling the conversion of propargylic alcohols into α,β-unsaturated ketones and esters. Under optimized conditions, high conversion

for a broad range of substrates was achieved. While being able to accommodate sterically demanding and deactivating substituents, the present catalytic system proved to be inappropriate for primary alcohols and terminal alkynes. On the other hand, stereoselectivity was found to range from good to excellent. A mechanism was proposed, suggesting activation of a water molecule instead of the C≡C triple bond. Furthermore, we observed formation of a furanone and an indanone derivative. These species raise interesting mechanistic issues in the context of gold(I)-catalysis. Due to the ease of preparation of propargylic alcohols, the gold(I)-catalyzed Meyer–Schuster rearrangement appears to be a promising tool to access α,β-unsaturated carbonyl compounds.

4. Experimental section

4.1. General information

All reagents were used as received. Reactions were performed under ambient atmosphere. Technical grade solvents were used. [(NHC)AuCl] complexes were synthesized as described in the literature.[27] Propargylic alcohols were synthesized as described in the literature[16] and purified by flash chromatography (silica 60 Å, Silicycle 230–400 mesh). ^{1}H and ^{13}C NMR spectra were recorded on a Bruker Avance 400 ULTRASHIELD NMR spectrometer at ambient temperature in $CDCl_3$ containing 0.03% TMS. Chemical shifts are given in parts per million (ppm) relative to $CDCl_3$ (^{1}H: 7.26 ppm, ^{13}C: 77.16 ppm). Coupling constants are given in hertz (Hz). High resolution mass spectra (HRMS) were recorded by the HRMS unit of the ICIQ (Tarragona) using ESI (Electron Spray Ionization). Gas chromatography (GC) was performed on an Agilent 6890N Gas Chromatograph.

4.2. General procedure

In a 4 mL vial equipped with a magnetic stirring bar [(IPr)AuCl] (3.1 mg, 5 μmol, 0.02 equiv) was dissolved in MeOH (1.70 mL). $AgSbF_6$ (1.7 mg, 5 μmol, 0.02 equiv) was added and the solution was stirred for 1 min. The propargylic alcohol **1** (0.25 mmol, 1 equiv) was added, followed by addition of distilled H_2O (300 μL). The reaction mixture was heated overnight at 60 °C. Volatile components were then removed under reduced pressure and the residue was dissolved in a 1:1 mixture of pentane and Et_2O. The solution was filtered over a plug of silica (~1 cm) and solvents were removed under reduced pressure. NMR yields were determined as follow: A defined amount (~0.2 mmol) of benzaldehyde was added as internal standard to the crude product. Reported yields are average of two runs. New compounds were additionally prepared in 0.5 mmol scale and purified by flash chromatography for complete characterization and isolated yields.

Compounds **2a**,[16] **2f**,[16] **2h**,[16] **2l**,[16] **2n**,[16] **2o**[16] and **2r$_b$**,[16] **2i$_a$**,[28] **2i$_b$**,[29] **2g**,[30] **2k**,[31] **2m**,[32] **2q$_a$**,[33] **2q$_b$**,[34] **2r$_a$**[35] and **2t**[36] were characterized by comparing their NMR spectra with the literature data.

4.3. (*E*)-1-(4-(Trifluoromethyl)phenyl)hept-1-en-3-one (2b)

The compound was prepared as described in the general procedure (81% isolated yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.65 (s, 4H, H^{Ar}), 7.55 (d, *J*=16.2 Hz, 1H, C^{Ar}–CH=), 6.79 (d, *J*=16.2 Hz, 1H, =CH–C=O), 2.68 (t, *J*=7.4 Hz, 2H, C=O–CH_2), 1.67 (m, 2H, CH_2–CH_2–CH_2), 1.39 (m, 2H, CH_2–CH_3), 0.95 (t, *J*=7.3 Hz, 3H, CH_3). ^{13}C NMR (100 MHz, $CDCl_3$): δ 200.3 (C), 140.4 (CH), 138.2 (C), 131.9 (q, *J*=32.52 Hz, *C*–CF_3), 128.5 (CH), 128.4 (CH), 126.0 (q, *J*=3.8 Hz, CH), 123.9 (q, *J*=272.2 Hz, CF_3), 41.2 (CH_2), 26.4 (CH_2), 22.6 (CH_2), 14.0 (CH_3). HRMS (ESI) calcd for $C_{14}H_{16}F_3O$ ($[M+H]^+$) 257.1153. Found 257.1166.

4.4. (*E*)-4-(3-Oxohept-1-enyl)benzonitrile (2c)

The compound was prepared as described in the general procedure (74% isolated yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.70–7.60 (m, 4H, H^{Ar}), 7.51 (d, *J*=16.2 Hz, 1H, C^{Ar}–CH=), 6.79 (d, *J*=16.2 Hz, 1H, =CH–C=O), 2.67 (t, *J*=7.4 Hz, 2H, C=O–CH_2), 1.66 (m, 2H, CH_2–CH_2–CH_2), 1.39 (m, 2H, CH_2–CH_3), 0.94 (t, *J*=7.3 Hz, 3H, CH_3). ^{13}C NMR (100 MHz, $CDCl_3$): δ 200.0 (C), 139.7 (CH), 139.1 (C), 132.8 (CH), 129.1 (CH), 128.7 (CH), 118.5 (C), 113.5 (C), 41.3 (CH_2), 26.3 (CH_2), 22.5 (CH_2), 14.0 (CH_3). HRMS (ESI) calcd for $C_{14}H_{16}NO$ ($[M+H]^+$) 214.1232. Found 214.1243.

4.5. (*E*)-1-(Benzo[*d*][1,3]dioxol-5-yl)hept-1-en-3-one (2d)

The compound was prepared as described in the general procedure (81% isolated yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.46 (d, *J*=16.0 Hz, 1H, C^{Ar}–CH=), 7.05 (d, *J*=1.4 Hz, 1H, H^{Ar}), 7.03 (dd, *J*=7.9 Hz, *J*=1.5 Hz, H^{Ar}), 6.82 (d, *J*=8 Hz, 1H, H^{Ar}), 6.58 (d, *J*=16.0 Hz, 1H, =CH–C=O), 6.01 (s, 2H, CH_2O_2), 2.63 (t, *J*=7.5 Hz, 2H, C=O–CH_2), 1.65 (m, 2H, CH_2–CH_2–CH_2), 1.37 (m, 2H, CH_2–CH_3), 0.94 (t, *J*=7.3 Hz, 3H, CH_3). ^{13}C NMR (100 MHz, $CDCl_3$): δ 200.7 (C), 149.9 (C), 148.5 (C), 142.2 (CH), 129.2 (C), 124.9 (CH), 124.6 (CH), 108.8 (CH), 106.7 (CH), 101.7 (CH_2), 40.9 (CH_2), 26.7 (CH_2), 22.6 (CH_2), 14.1 (CH_3). HRMS (ESI) calcd for $C_{14}H_{17}O_3$ ($[M+H]^+$) 233.1178. Found 233.1173.

4.6. (*E*)-1-(Naphthalen-1-yl)hept-1-en-3-one (2e)

The compound was prepared as described in the general procedure (92% isolated yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.41 (d, *J*=15.9 Hz, 1H, C^{Ar}–CH=), 8.20 (d, *J*=8.3 Hz, 1H, H^{Ar}), 7.90 (t, *J*=5.3 Hz, 2H, H^{Ar}), 7.78 (d, *J*=7.2 Hz, 1H, H^{Ar}), 7.62–7.46 (m, 3H, H^{Ar}), 6.85 (d, *J*=15.9 Hz, 1H, =CH–C=O), 2.74 (t, *J*=7.4 Hz, 2H, C=O–CH_2), 1.73 (tt, 2H, CH_2–CH_2–CH_2), 1.43 (tq, 2H, CH_2–CH_3), 0.98 (t, *J*=7.3 Hz, 3H, CH_3). ^{13}C NMR (100 MHz, $CDCl_3$): δ 200.6 (C), 139.2 (CH), 133.8 (C), 132.1 (C), 131.7 (C), 130.7 (CH), 128.9 (CH), 128.8 (CH), 127.0 (CH), 126.4 (CH), 125.6 (CH), 125.1 (CH), 123.4 (CH), 41.2 (CH_2), 26.6 (CH_2), 22.6 (CH_2), 14.1 (CH_3). HRMS (ESI) calcd for $C_{17}H_{19}O$ ($[M+H]^+$) 239.1436. Found 239.1443.

4.7. 4-Methoxy-5-phenylfuran-2(5*H*)-one (2j)

The compound was prepared as described in the general procedure (69% isolated yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.42–7.36 (m, 3H, H^{Ar}), 7.35–7.29 (m, 2H, H^{Ar}), 5.69 (s, 1H, Ph–CH), 5.16 (s, 1H, CH–C=O), 3.85 (s, 3H, OCH_3). ^{13}C NMR (100 MHz, $CDCl_3$): δ 181.8 (C), 172.7 (C), 134.1 (C), 129.6 (CH), 129.0 (CH), 126.8 (CH), 88.4 (CH), 80.4 (CH), 59.7 (CH_3).

4.8. (*E*)-1-(3-Fluorophenyl)hex-2-en-1-one (2p)

The compound was prepared as described in the general procedure (89% isolated yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.70 (m, 1H, H^{Ar}), 7.61 (m, 1H, H^{Ar}), 7.44 (m, 1H, H^{Ar}), 7.24 (m, 1H, H^{Ar}), 7.09 (td, $^3J_1$=15.4 Hz $^3J_2$=7.0 Hz, 1H, CH_2–*CH*=CH), 6.83 (td, ^3J=15.4 Hz, ^4J=1.5 Hz, 1H, CH_2=*CH*–C=O), 2.30 (m, 2H, CH_2–CH=), 1.56 (m, 2H, CH_2–CH_3), 0.98 (t, *J*=7.4 Hz, 3H, CH_3). ^{13}C NMR (100 MHz, $CDCl_3$): δ 189.6 (d, *J*=2.2 Hz, C), 162.9 (d, *J*=247.6 Hz, C), 150.8 (CH), 140.2 (d, *J*=6.3 Hz, C), 130.2 (d, *J*=7.8 Hz, CH), 125.7 (CH), 124.3 (d, *J*=2.9 Hz, CH), 119.6 (d, *J*=21.6 Hz, CH), 115.4 (d, *J*=22.3 Hz, CH), 34.9 (CH_2), 21.5 (CH_2), 13.8 (CH_3). HRMS (ESI) calcd for $C_{12}H_{14}FO$ ($[M+H]^+$) 193.1029. Found 193.1039.

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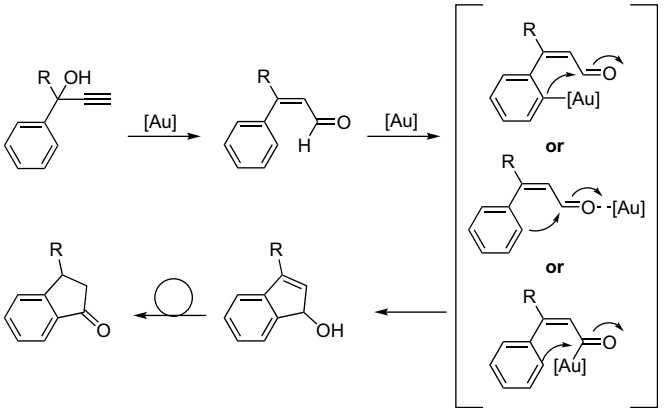

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