Gold Trifluoromethyl Complexes as Efficient Regioselective Catalysts in Alkyne Hydration

David Ruiz-Almoguera,[a] David Ventura-Espinosa,[a] Alberto Pérez-Bitrián,[b, c] Antonio Martín,[b] José A. Mata,*[a] and Miguel Baya*[b]

Gold(III) complexes containing trifluoromethyl ligands are efficient catalysts in the hydration of alkynes, operating at low catalyst loadings, without additives, using environmentally friendly solvents and at mild conditions (60 °C). Hydration of terminal and internal alkynes provides the corresponding ketones in quantitative yields without special precautions as dry solvents or inert atmospheres. Remarkably, hydration of asymmetric internal alkynes proceeds with moderate to notable regioselectivities, providing mixtures of the two possible isomers with ratios up to 90:10.

Introduction

Development of synthetic protocols in harmony with sustainability principles constitutes a desired goal. The 12 principles of Green Chemistry of Anastas & Warner provide an excellent guide.[1,2] Aspects as the use of low catalyst loadings in atom-economical reactions, operating at mild conditions in environmentally-friendly solvents and in the absence of additives, become requisites in catalysis. Furthermore, attaining a high regioselectivity in these reactions is a tremendously desirable target, if not even still a challenge in some transformations.

In this context, gold chemistry can offer competitive solutions for the design of efficient transformations,[3–5] which are indeed arising as a powerful tool in the development of sustainable catalytic reactions.[6–9] During the last two decades there has been an outstanding uprise of the applications of gold(I) catalysts for a wide range of reactions.[10–12] Conversely, exploration of the potential of gold(III) complexes in catalysis is still in its infancy and the number of examples is scarce.[13–16] The reason is attributed to the low thermal stability of gold(III) complexes and the requirement of high catalysts loadings in most transformations.[9] Nevertheless, design of gold(III) complexes holds great promise, as gold in oxidation state +3

possess a marked Lewis acidity which is associated with the origin of many gold-catalyzed transformations. Gold catalysis would be improved by complementing the well-known transformations of gold(I) with complementary reactivity and selectivity issues imposed by gold(III) species.

Nucleophilic additions to unsaturated hydrocarbons constitute a powerful tool for the functionalization of organic substrates.[17–19] In particular, hydration of alkynes is a well-known reaction that allows the introduction of an oxygen functionality into hydrocarbons, and has become a benchmark reaction for testing the potential of metal catalysts towards nucleophilic additions to multiple bonds.[20–24] The performance of gold(I) catalysts in alkyne hydration has been widely explored in the scientific literature (Figure 1), becoming a safer alternative than the initially used mercury salts,[25] and requiring very low catalyst loadings, occasionally below 0.1%. Nevertheless, incomplete conversions, the need of additives or solvents other than alcohols and water, and/or the design of sophisticated ligands are the main drawbacks.[26–30]

On the other hand, few reports on gold(III)-catalyzed alkyne hydration have been described (Figure 1).[31–36] Fukuda and

[a] D. Ruiz-Almoguera, D. Ventura-Espinosa, J. A. Mata
Institute of Advanced Materials (INAM), Universitat Jaume I, Avda. Sos Baynat s/n, 12006 Castellón, (Spain)
E-mail: jmata@uji.es

[b] A. Pérez-Bitrián, A. Martín, M. Baya
Instituto de Síntesis Química y Catálisis Homogénea (iSQCH), CSIC-Universidad de Zaragoza, C/Pedro Cerbuna 12, 50009 Zaragoza, (Spain)
E-mail: mbaya@unizar.es

[c] A. Pérez-Bitrián
Current address: Institut für Chemie, Humboldt-Universität zu Berlin, Brook-Taylor-Straße 2, 12489 Berlin, (Germany)

Figure 1. State-of-the-art of gold-catalyzed alkyne hydration.

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Utimoto first described the hydration of terminal and internal alkynes promoted by Na[AuCl$_4$] in 1991.[33] Laguna achieved the hydration of phenylacetylene and *n*-heptyne by using Au(III) pentafluorophenyl derivatives,[32] whereas López de Luzuriaga analyzed the hydration of alkynes promoted by dithiocarbamate gold(III) complexes.[35] A salen-gold(III) complex was also reported by the group of Cai to catalyze the hydration of a wide variety of terminal alkynes in MeOH, yet trifluoroacetic acid was required as cocatalyst.[36] More recently, Belanzoni, Zuccaccia and coworkers reported on the use of [Au^{III}Cl-(NHC)(ppy)]$^+$ complexes (NHC = 1,3-bis(2,6-di-isopropylphenyl)-imidazol-2-ylidene; ppy = 2-phenylpyridine) for the catalytic hydration of alkynes such as γ-valerolactone under acid-free conditions, although AgOTf was needed as additive.[31] The relevance of this work also stems from the experimental proof for the mechanism of this transformation. The first step consists in alkyne activation by π coordination to the acidic Au(III) center. Then the alkyne undergoes the nucleophilic attack of a water molecule.

State-of-the-art challenges relative to sustainable alkyne hydration deal with suppression of additives and attainment of regioselectivity when using asymmetric internal alkynes,[37–39] which is a particularly serious issue in gold-catalyzed processes.[40] Furthermore, this becomes even more problematic when trying to keep low catalyst loadings while preserving activity. In this regard, gold(III) catalysts offer excellent opportunities for fulfilling all these requirements. Also, the design of these type of catalysts has an added value, based on the very few precedents known so far.

In recent years, the use of strong electron donating, chelate and pincer ligands, to stabilize gold (III) systems has emerged as a useful strategy for the preparation of a plethora of gold(III) complexes. An alternative strategy makes use of perfluoroalkyl ligands, as for example the trifluoromethyl.[41] Within the recent uprise of gold trifluoromethyl compounds,[42] the chemistry of the {Au(CF$_3$)$_3$} moiety has been significantly broadened, with a number of anionic and neutral complexes reported in the last decade.[43–49] Complementarily, compounds containing the *trans*-{Au(CF$_3$)$_2$} scaffold have become also easily accessible.[50,51] The 14 valence electron Au(CF$_3$)$_3$ fragment has been assessed to have a Lewis acidity similar to that of B(C$_6$F$_5$) or AsF$_5$, therefore merging the high Lewis acidity of very efficient catalysts of widespread use and the advantages of gold complexes.[44] Additionally, it provides a very rigid scaffold with a high stereochemical stability. In particular, neutral complexes of the type Au(CF$_3$)$_3$L offer a wide range of stabilities depending on the L ligand, while at the same time allowing the tunability of its lability in solution. In this regard, Au(CF$_3$)$_3$(MeCN) and Au(CF$_3$)$_3$(THT) show remarkable properties, as they are labile in solution allowing easy interchange of the neutral ligands, yet thermally stable, subliming above 160 °C. All these arguments suggest that these complexes might be excellent catalysts for nucleophilic addition reactions to multiple bonds, which would be activated upon coordination to this highly acidic Au(III) unit.

In this work we describe the catalytic properties of Au^{III} complexes bearing CF$_3$ ligands in hydration of alkynes. We assess the influence of reaction conditions, heterogeneity issues

and specially the regioselectivity in the hydration of asymmetric internal alkynes.

Results and Discussion

We evaluated the catalytic properties of Au(III) complexes in the benchmark reaction of hydration of alkynes. Among a series of trifluoromethyl gold(III) complexes in our library, we selected the anionic trans-[Au(CF$_3$)$_2$X$_2$]$^-$ (X=Cl, Br) and the neutral Au(CF$_3$)$_3$L (L=acetonitrile (MeCN) or tetrahydrothiophene (THT)) complexes as representative examples and potential candidates as catalysts (Figure 2).[50,51] The trifluoromethyl complexes are more stable than the methyl analogues in solution and in the solid state. Single crystals of **1** suitable for X-ray diffraction were obtained by slow diffusion of a layer of n-hexane (5 mL) into a saturated solution of **1** in CH$_2$Cl$_2$ (2 mL) at −30 °C (Figure S3).

We studied the catalytic performance of four selected complexes in the hydration of alkynes using phenylacetylene as model substrate (Figure 2). The monitoring reaction profiles showed that the neutral catalysts (**1** & **2**) containing a labile ligand (MeCN or THT) were notably more active than the anionic ones, which were consequently discarded for further studies. The absence of a vacant coordination site prevents metal-substrate interaction inhibiting the reaction. Both neutral catalysts showed analogous activities independent of the labile ligand, so we finally chose complex Au(CF$_3$)$_3$(MeCN) (**1**) as representative gold complex. It is important to note that HAuCl$_4$ displayed a modest activity (< 10%) in the hydration of phenyl-acetylene implying a limited activity for a representative gold-(III) complex.
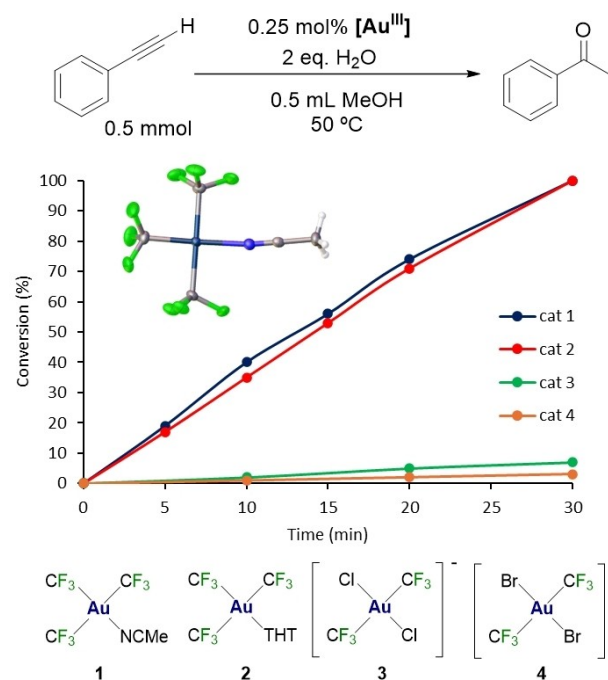

Figure 2. Comparative catalyst activity in hydration of phenylacetylene. Inset: ORTEP diagram of complex **1**.

In a first set of experiments to optimize the reaction conditions we selected phenylacetylene as model substrate. Gold-catalyzed alkyne hydration requires the use of polar solvents (normally MeOH) miscible with water. We first analyzed the amount of water required in the hydration of phenylacetylene. The water amount is an important parameter to consider in hydration, as a large amount of this reagent may cause catalyst deactivation or solubility problems that inhibit product formation. As general conditions, a series of 3.5 mL methanol solutions containing 0.5 mmol of phenylacetylene and a catalyst loading of 0.25 mol% of complex Au(CF$_3$)$_3$(MeCN) were heated at 60 °C, and different quantities of water were added (Figure S4). For this set of experiments, we used commercial dry MeOH ($<0.005\%$ of water) which was stored under activated 3 Å molecular sieves. Without the addition of water, the yield was less than 20% indicating that the dry solvent contains some water and that effectively water is required for the hydration of alkynes. The addition of 1 eq. of water improves the yield up to 60%. The best results were obtained when using 2 eq. of water that provided quantitative yield in 60 min. It is interesting to note that the addition of more equivalents of water (4 eq.) is detrimental for the reaction and lower yields were observed (Figure S4).

Then, we determined the optimal substrate concentration for the reaction. As general conditions we prepared a series of methanol solutions (0, 0.5, 1, 2, and 3.5 mL) containing 0.5 mmol of phenylacetylene, 2 eq. of water and the samples were heated up to 60 °C. Among all the conditions tested, the most concentrated (1 M) provided better outcomes and the reaction was completed in only 30 min (Figure S5). It is important to note that hydration of alkynes also evolves in the absence of solvent, highlighting the convenience of Au^{III} complexes for this transformation.

We also assessed the effect of temperature in the hydration of alkynes (Figure S6). In this case we prepared a set of 0.5 mL methanol solutions containing 0.5 mmol of phenylacetylene, 2 eq. of water and a 0.25 mol% catalyst loading. At 60 °C the reaction was completed after 30 min, whereas at 50 °C the reaction was completed only after 90 min. The hydration of phenylacetylene also evolves at 40 °C providing quantitative yields in 250 min. We have observed that this is the minimum working temperature as the reaction did not evolve at 30 °C. Thus, we set 60 °C as a convenient reaction temperature for hydration of alkynes. We also used these variable temperature experiments to estimate the Gibbs free energy of activation. We use a recently developed graphical method for determining the transition state enthalpy and entropy (Figures S7 and S8).[52] The results provide an estimation of $\Delta G^{\neq}$ of 91.7 KJ/mol that agrees with the experimental observations.

Complementary, poisoning tests were performed in order to determine whether the reaction is homogeneous or heterogeneous in nature. For this purpose, we used mercury as a scavenger of heterogeneous gold species and polyvinyl pyridine (PVP) as a scavenger of molecular gold species. Three parallel experiments were conducted using the general reaction conditions and, after 15 min, the scavengers were added to the first and second reaction mixtures leaving the third as a control

experiment (Figure S10). The results showed that the reaction is only inhibited in the presence of PVP experiment, whereas the mercury experiment continued at a similar rate to that of the control experiment. These results support the homogeneous nature of Au^{III} species in the hydration of alkynes.

Hydration of Terminal Alkynes

The gold(III) complex Au(CF$_3$)$_3$(MeCN) (**1**) contains a labile ligand, allowing easy acetonitrile exchange by alkyne substrate. The homoleptic fragment Au(CF$_3$)$_3$ modulates the electronic and steric properties of the catalytic system. In addition, the presence of CF$_3$ ligands confers enhanced stability. Once established the basics of our catalytic system, we focused on determining the scope of the reaction. We tested the reaction scope in up to eleven different terminal alkynes, including aliphatic and aromatic acetylenes, and also possessing different types of substituents. Notably, for nine of them we observed full conversion in less than 1 hour using low catalyst loadings (Figure 3). Indeed, we achieved isolated yields higher than 90% in these nine studied cases (Figures S11–S21). Remarkably, no need of additives is required in the reaction mixtures to perform these transformations and the temperature required is mild (50 °C). These results evidence that gold(III) complex **1** is an efficient catalyst in the hydration of terminal alkynes from a sustainable point of view.
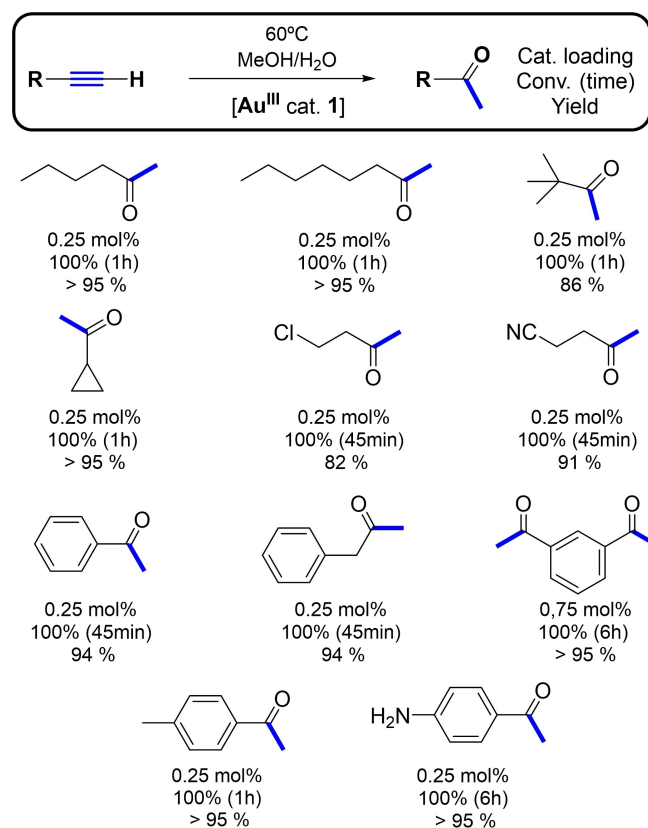

Figure 3. Gold(III) catalyzed (**1**) hydration of terminal alkynes. Conditions: alkyne (0.5 mmol), MeOH (0.5 mL), H$_2$O (2 eq.).

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Hydration of Symmetric Internal Alkynes

Hydration of terminal alkynes may produce two different regioisomers. It is well established that hydration of terminal alkynes proceeds with high selectivity to render Markovnikov-type ketones, that is, methyl ketones. As a rational extension of the work, we assessed the hydration of internal alkynes. We first tested symmetric alkynes as only one isomer is possible. We used 3-hexyne, 4-octyne, and diphenylacetylene as representative examples of internal alkynes (Figure 4). The results revealed conversions of 100% and yields above 90%, when using catalyst loadings between 0.5 and 0.75 mol% at 60°C (Figures S22–S24). Internal alkynes are less reactive than terminal and the hydration of symmetric internal alkynes requires prolonged reaction times but also provided quantitative yields using **1**.

Hydration of Asymmetric Internal Alkynes

In the case of internal asymmetric alkynes, two different regioselective ketone products are possible. Design of catalysts that induce regioselectivity in hydration of alkynes is a difficult task and still needs improvement. We used propyl-phenyl-acetylene as model substrate to explore the capacities of gold complex **1** in the induction of selectivity in hydration of alkynes
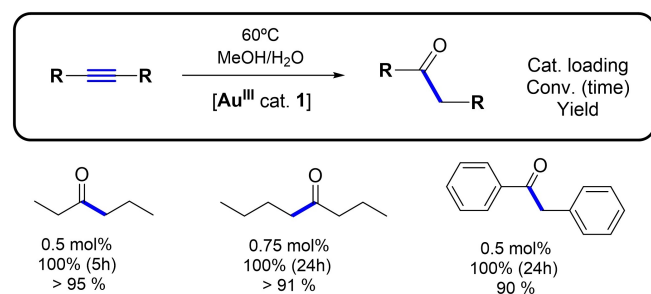
(Figure 5). The hydration proceeds smoothly, and quantitative yield is obtained after 20 h. The ^{1}H NMR spectrum of the reaction crude reveals the formation only of both regioisomers without the presence of other side products. The Au-$(CF_3)_3$(MeCN) complex favors the formation of the regioisomer where the carbonyl group is closer to the aromatic ring (1-phenylpentan-1-one) in 77% vs. the 1-phenylpentan-2-one that is obtained only in 23% yield.

In view of these results, we extended our studies to other asymmetric internal alkynes bearing alkyl and/or aryl substituents to evaluate the reaction scope (Figure 6). In all cases, 100% conversion and quantitative yields were obtained. The regioselectivities observed range from 63:37 to 90:10 (Figures S25–S29). The lowest regioselectivity was obtained in the hydration of 2-hexyne, an asymmetric alkyne containing a methyl and a propyl group (Figure 6, entry 1). As both alkyl substituents are similar in electronic and steric properties the low regioselectivity (63:37) was not unexpected. Interestingly, when exchanging the propyl by an iso-propyl group (Figure 6, entry 2), the regioselectivity increases up to 81:19 product distribution. Small changes in steric properties of substrates have an important effect on regioselectivity. However, assessment of temperature and catalyst loading influence on regioselectivity provided similar results. Reducing the reaction temperature to 40°C or doubling the amount of catalyst loading up to 0.5 mol% provided similar regioselectivities (Figure 6, entry 2). The best result in terms of regioselectivity was obtained in the hydration of methyl-phenylacetylene (90:10) a substrate containing two alkyne substituents of different nature in both, electronic and steric effects (Figure 6, entry 3). When the methyl group is replaced by a propyl group the major product is again the phenyl ketone (Figure 6, entry 5). However, for the alkyne containing an ethyl group, the regioselectivity is reversed and

Figure 4. Gold(III) catalyzed (**1**) hydration of internal alkynes. Conditions: alkyne (0.5 mmol), MeOH (0.5 mL), H_2O (2 eq.).
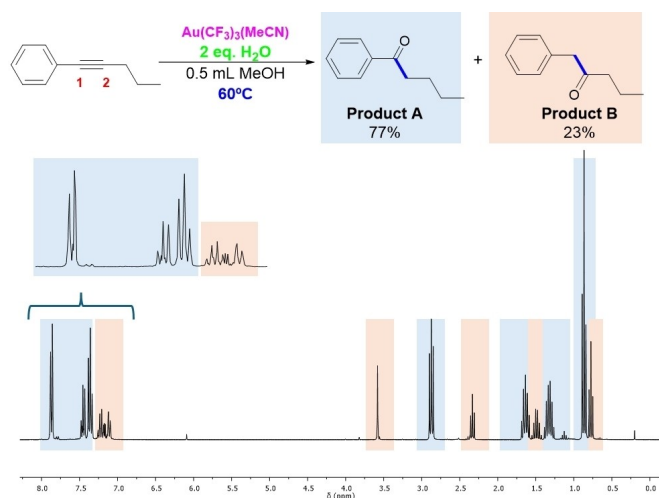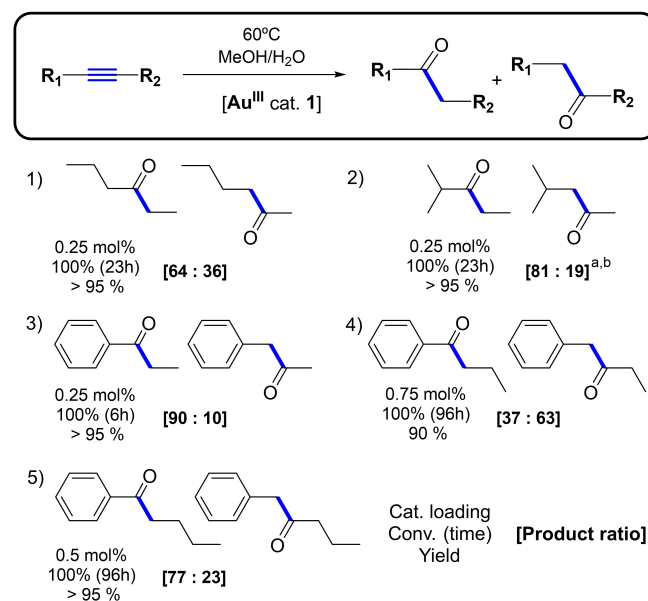

Figure 5. Regioselectivity of **1** in hydration of asymmetric internal alkynes. Conditions: alkyne (0.5 mmol), MeOH (0.5 mL), H_2O (2 eq.) and **1** (0.5 mol%).

Figure 6. Gold(III) catalyzed (**1**) hydration of internal alkynes. Conditions: alkyne (0.5 mmol), MeOH (0.5 mL), H_2O (2 eq.). a) Similar regioselectivity was obtained at 40°C. b) Similar regioselectivity was obtained using a 0.5 mol% catalyst loading.

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the major product is the benzyl ketone. We tried to explain the divergent regioselectivity by assessing the temperature influence and/or catalyst loading but the results were not conclusive. At this point we do not have a proper explanation for the divergent regioselectivity obtain for ethyl-phenylacetylene (Figure 6, entry 4) and further mechanistic studies are required. The gold(III) complex **1** is an efficient and regioselective catalyst in hydration of alkynes whose properties are markedly induced by substrate steric properties.

Conclusions

A gold(III) complex bearing trifluoromethyl ligands behaves as a catalyst in a sustainable hydration of alkynes. These include low catalyst loadings, high efficiency and reaction yields, no need of additives, mild conditions and environmentally friendly solvents. The square-planar $Au(CF_3)_3(MeCN)$ complex is capable of providing moderate to notable regioselectivities in the hydration of asymmetric internal alkynes without sophisticated ligand design. The results obtained strongly support that perfluoroalkyl gold(III) species are promising candidates for achieving highly regioselective alkyne hydration of alkynes, a scientific challenge that has not been fully accomplished so far.

Experimental

General Information

Unless otherwise stated, gold complexes were prepared under purified argon by using Schlenk techniques. Solvents were dried with an MBraun SPS-800 System. Compounds $[PPh_4][trans\text{-}Au(CF_3)_2X_2]$ (X=Cl, Br),[50] $[PPh_4][Au(CF_3)_3I]$[43] and $Au(CF_3)_3(THT)$,[44] were prepared following literature procedures. Other chemicals were purchased from standard commercial suppliers and used as received. NMR spectra were recorded with a Bruker AV 400 spectrometer at room temperature. Chemical shifts are given with respect to the standard references: $SiMe_4$ (^1H) and $CFCl_3$ (^{19}F). Chemically inequivalent CF_3 groups are indicated as follows: CF_3-M-NCMe refers to the CF_3 group trans to the MeCN ligand, whereas CF_3-M–CF_3 refers to the mutually trans-standing CF_3 groups. Multiplicity is indicated as follows: s=singlet, q=quartet, spt=septet.

Synthesis of 1

The synthesis of $Au(CF_3)_3(MeCN)$ is based on a literature-known procedure[44] and was scaled up. An equimolar amount of $AgClO_4$ (0.24 mg, 1.15 mmol) was added to a solution of $[PPh_4][Au(CF_3)_3I]$ (1.00 g, 1.15 mmol) in CH_2Cl_2/Et_2O (2/40 mL) in the dark, causing immediate precipitation of AgI. After 30 min of stirring, the solvent mixture was replaced by Et_2O/n-hexane (20/60 mL), and the resulting suspension was kept at $-80\,^\circ C$ overnight. Filtering off all solid side products allowed to obtain a solution of $Au(CF_3)_3\cdot OEt_2$ (0.92 mmol), to which MeCN (48 μL, 0.92 mmol) was then added. After 30 min of stirring, the solvent was removed by vacuum evaporation, affording a white solid. To achieve a higher purity, this crude material was dissolved in CH_2Cl_2 (10 mL) and filtered through celite©. The colorless filtrate was evaporated to dryness, rendering a white solid, which was suspended in n-hexane (5 mL), collected by filtration, washed with more n-hexane (2×3 mL), dried, and identified as **1** (388 mg, 0.87 mmol, 76% yield). ^1H **NMR** (400.130 MHz, CD_2Cl_2, 298 K, Figure S1): δ_H/ppm = 2.53 (s; CH_3). ^{19}F **NMR** (376.308 MHz, CD_2Cl_2, 298 K, Figure S2): δ_F/ppm = -27.47 [spt, 3F, $^4J(F,F)$ = 6.7 Hz; CF_3-Au-NCMe], -35.73 (q, 6F; $^4J(F,F$ = 6.7 Hz CF_3-Au-CF_3).

Catalytic Experiments

In a general catalytic experiment, 0.5 mmol of the alkyne, 1 mmol of distilled water, the necessary amount of catalyst required for the experiment and 0.5 mL of methanol were placed into a high-pressure Schlenk tube (50 mL) closed with a screw Teflon cap. The Schlenk tube was introduced in the oil bath at $60\,^\circ C$ with continuous agitation. All catalytic experiments were repeated at least twice. Conversion of alkyne into the corresponding ketone was monitored by gas chromatography (GC) using 0.5 mmol of anisole as an internal standard. GC analyses were obtained on a Shimadzu GC-2010 apparatus equipped with a FID detector, and using a Teknokroma column (TRB-5MS, 30 m×0.25 mm×0.25 μm). After drying at reduced pressure, the organic products were characterized by ^1H NMR without further purification. Yield was calculated using 0.25 mmol of of 1,3,5-trimethoxybenzene (TMB) as an external standard.

Crystallographic Data

Deposition Number 2351747 for **1**, contains the supplementary crystallographic data for this paper. These data are provided free of charge by the joint Cambridge Crystallographic Data Centre and Fachinformationszentrum Karlsruhe Access Structures service.

Supporting Information Summary

The Supporting Information contains characterization NMR spectra of **1**, single crystal X-ray diffraction data, additional catalytic experiments, and NMR characterization of crude reaction products. Additional references within the Supporting Information.[53–74]

Conflict of Interests

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

[1] J. C. Anastas, T. Paul, Warner, *Green Chem. Theory Pract.*, Oxford University Press, Oxford, UK, **1998**

[2] P. Anastas, N. Eghbali, *Chem. Soc. Rev.* **2010**, *39*, 301–312.

[3] R. P. Herrera, M. C. Gimeno, *Chem. Rev.* **2021**, *121*, 8311–8363.

[4] A. Corma, H. Garcia, *Chem. Soc. Rev.* **2008**, *37*, 2096–2126.

[5] A. S. K. Hashmi, G. J. Hutchings, *Angew. Chem. Int. Ed.* **2006**, *45*, 7896–7936.

[6] K. S. Egorova, V. P. Ananikov, *Angew. Chem. Int. Ed.* **2016**, *55*, 12150–12162.

[7] D. Ventura-Espinosa, S. Martín, J. A. Mata, *J. Catal.* **2019**, *375*, 419–426.

[8] A. Collado, A. Gómez-Suárez, S. P. Nolan, in *Chapter 16. Sustain. Homog. Gold Catal.*: With Non-endangered Metals, Part 2, ed. M. North and M. North, The Royal Society of Chemistry **2015**, ch. 16, pp. 41–90.

[9] A. Kumar, N. T. Patil, *ACS Sustainable Chem. Eng.* **2022**, *10*, 6900–6918.

[10] A. G. Tathe, S. S. Saswade, N. T. Patil, *Org. Chem. Front.* **2023**, *10*, 2359–2384.

[11] S. R. Mudshinge, Y. Yang, B. Xu, G. B. Hammond, Z. Lu, *Angew. Chem. Int. Ed.* **2022**, *61*, 1–7.

[12] L. Rocchigiani, M. Jia, M. Bandini, A. Macchioni, *ACS Catal.* **2015**, *5*, 3911–3915.

[13] J. Rodriguez, D. Bourissou, *Angew. Chem. Int. Ed.* **2018**, *57*, 386–388.

[14] L. Rocchigiani, M. Bochmann, *Chem. Rev.* **2021**, *121*, 8364–8451.

[15] Z. Zheng, X. Ma, X. Cheng, K. Zhao, K. Gutman, T. Li, L. Zhang, *Chem. Rev.* **2021**, *121*, 8979–9038.

[16] H. Schmidbaur, A. Schier, *Arab. J. Sci. Eng.* **2012**, *37*, 1187–1225.

[17] E. Jiménez-Núñez, A. M. Echavarren, *Chem. Commun.* **2007**, *4*, 333–346.

[18] Z. Li, C. Brouwer, C. He, *Chem. Rev.* **2008**, *108*, 3239–3265.

[19] A. Arcadi, *Chem. Rev.* **2008**, *108*, 3266–3325.

[20] C. H. Leung, M. Baron, A. Biffis, *Catalysts* **2020**, *10*, 1–35.

[21] D. Zuccaccia, A. Del Zotto, W. Baratta, *Coord. Chem. Rev.* **2019**, *396*, 103–116.

[22] P. Gao, M. Szostak, *Coord. Chem. Rev.* **2023**, *485*, 215110.

[23] D. Ventura-Espinosa, S. Martín, H. García, J. A. Mata, *J. Catal.* **2021**, *394*, 113–120.

[24] M. Cloutier, M. Roudias, J.-F. Paquin, *Org. Lett.* **2019**, *21*, 3866–3870.

[25] J. H. Teles, in *Mod. Gold Catalyzed Synth.*, eds. Prof, Dr. A. Stephen K. Hashmi and Prof. F. Dean Toste, Wiley **2012**, pp. 201–235.

[26] M. Heidrich, M. Bergmann, D. Müller-Borges, H. Plenio, *Adv. Synth. Catal.* **2018**, *360*, 3572–3578.

[27] M. Inoue, K. Ugawa, T. Maruyama, T. Iwasawa, *Eur. J. Org. Chem.* **2018**, *2018*, 5304–5311.

[28] N. Marion, R. S. Ramón, S. P. Nolan, *J. Am. Chem. Soc.* **2009**, *131*, 448–449.

[29] M. Gatto, P. Belanzoni, L. Belpassi, L. Biasiolo, A. Del Zotto, F. Tarantelli, D. Zuccaccia, *ACS Catal.* **2016**, *6*, 7363–7376.

[30] M. Navarro, M. Holzapfel, J. Campos, *Chempluschem* **2023**, *88*, 1–7.

[31] J. Segato, A. Del Zotto, L. Belpassi, P. Belanzoni, D. Zuccaccia, *Catal. Sci. Technol.* **2020**, *10*, 7757–7767.

[32] R. Casado, M. Contel, M. Laguna, P. Romero, S. Sanz, *J. Am. Chem. Soc.* **2003**, *125*, 11925–11935.

[33] Y. Fukuda, K. Utimoto, *J. Org. Chem.* **1991**, *56*, 3729–3731.

[34] R. O. C. Norman, W. J. E. Parr, C. B. Thomas, *J. Chem. Soc. Perkin Trans. 1* **1976**, *833*, 1983–1987.

[35] J. Cordón, G. Jiménez-Osés, J. M. López-de-Luzuriaga, M. Monge, M. E. Olmos, D. Pascual, *Organometallics* **2014**, *33*, 3823–3830.

[36] T. Chen, C. Cai, *Catal. Commun.* **2015**, *65*, 102–104.

[37] X. Liu, J.-L. Pozzo, M. Hamze, M. Alami, O. Provot, *ACS Catal.* **2023**, *13*, 10115–10136.

[38] R. Gauthier, N. V. Tzouras, S. P. Nolan, J.-F. Paquin, *Chem. Commun.* **2023**, *59*, 9138–9141.

[39] J.-D. Hamel, T. Hayashi, M. Cloutier, P. R. Savoie, O. Thibeault, M. Beaudoin, J.-F. Paquin, *Org. Biomol. Chem.* **2017**, *15*, 9830–9836.

[40] J. A. Goodwin, A. Aponick, *Chem. Commun.* **2015**, *51*, 8730–8741.

[41] M. A. García-Monforte, S. Martínez-Salvador, B. Menjón, *Eur. J. Inorg. Chem.* **2012**, *2012*, 4945–4966.

[42] J. Gil-Rubio, J. Vicente, *Dalton Trans.* **2015**, *44*, 19432–19442.

[43] A. Pérez-Bitrián, S. Martínez-Salvador, M. Baya, J. M. Casas, A. Martín, B. Menjón, J. Orduna, *Chem. – A Eur. J.* **2017**, *23*, 6919–6929.

[44] A. Pérez-Bitrián, M. Baya, J. M. Casas, L. R. Falvello, A. Martín, B. Menjón, *Chem. - A Eur. J.* **2017**, *23*, 14918–14930.

[45] P. Golz, K. Shakeri, L. Maas, M. Balizs, A. Pérez-Bitrián, H. D. Kemmler, M. Kleoff, P. Voßnacker, M. Christmann, S. Riedel, *Chem. – A Eur. J.* **2024**, *30*, e202400861, DOI 10.1002/chem.202400861.

[46] M. Winter, N. Limberg, M. A. Ellwanger, A. Pérez-Bitrián, K. Sonnenberg, S. Steinhauer, S. Riedel, *Chem. – A Eur. J.* **2020**, *26*, 16089–16097.

[47] A. Pérez-Bitrián, M. Baya, J. M. Casas, A. Martín, B. Menjón, *Dalton Trans.* **2021**, *50*, 5465–5472.

[48] A. Pérez-Bitrián, S. Alvarez, M. Baya, J. Echeverría, A. Martín, J. Orduna, B. Menjón, *Chem. – A Eur. J.* **2023**, *29*, e202203181.

[49] D. Wegener, A. Pérez-Bitrián, N. Limberg, A. Wiesner, K. F. Hoffmann, S. Hasenstab-Riedel, *Chem. – A Eur. J.* **2024**, *30*, e202401231. DOI: 10.1002/chem.202401231.

[50] S. Martínez-Salvador, L. R. Falvello, A. Martín, B. Menjön, *Chem. - A Eur. J.* **2013**, *19*, 14540–14552.

[51] A. Pérez-Bitrián, M. Baya, J. M. Casas, A. Martín, B. Menjón, J. Orduna, *Angew. Chem. Int. Ed.* **2018**, *57*, 6517–6521.

[52] M. Rivero-Crespo, J. Oliver-Meseguer, K. Kapłońska, P. Kuśtrowski, E. Pardo, J. P. Cerón-Carrasco, A. Leyva-Pérez, *Chem. Sci.* **2020**, *11*, 8113–8124.

[53] *CrysAlis RED, CCD Camera Data Reduction Program*, Rigaku Oxford Diffraction, Oxford, UK **2019**.

[54] G. M. Sheldrick, *Acta Crystallogr. Sect. A Found. Adv.* **2015**, *71*, 3–8.

[55] Y.-X. Chen, J.-T. He, M.-C. Wu, Z.-L. Liu, K. Tang, P.-J. Xia, K. Chen, H.-Y. Xiang, X.-Q. Chen, H. Yang, *Org. Lett.* **2022**, *24*, 3920–3925.

[56] K. Martina, M. J. Moran, M. Manzoli, M. V. Trukhan, S. Kuhn, T. Van Gerven, G. Cravotto, *Org. Process Res. Dev.* **2024**, *28*, 1515–1528.

[57] M. Trinchillo, P. Belanzoni, L. Belpassi, L. Biasiolo, V. Busico, A. D'Amora, L. D'Amore, A. Del Zotto, F. Tarantelli, A. Tuzi, D. Zuccaccia, *Organometallics* **2016**, *35*, 641–654.

[58] J. R. Cabrero-Antonino, A. Leyva-Pérez, A. Corma, *Chem. – A Eur. J.* **2012**, *18*, 11107–11114.

[59] S. Maciuk, S. H. Wood, V. K. Patel, P. D. P. Shapland, N. C. O. Tomkinson, *Chem. – A Eur. J.* **2023**, *29*, DOI 10.1002/chem.202204007.

[60] R. Gompper, H. Vogt, *Chem. Ber.* **1981**, *114*, 2866–2883.

[61] S. Chandrasekhar, A. Shrinidhi, *Synth. Commun.* **2014**, *44*, 1904–1913.

[62] X. Chang, X. Cheng, X. Liu, C. Fu, W. Wang, C. Wang, *Angew. Chem. Int. Ed.* **2022**, *61*, DOI 10.1002/anie.202206517.

[63] Y. Li, T. Yang, S. Wang, Z. Bian, Z. Liu, *Green Chem.* **2024**, *26*, DOI 10.1039/d3gc04314b.

[64] T. V. Chciuk, W. R. Anderson, R. A. Flowers, *Organometallics* **2017**, *36*, 4579–4583.

[65] X. Yang, Y. Guo, H. Tong, H. Guo, R. Liu, R. Zhou, *Org. Lett.* **2023**, *25*, 5486–5491.

[66] L. Tao, X. Guo, J. Li, R. Li, Z. Lin, W. Zhao, *J. Am. Chem. Soc.* **2020**, *142*, 18118–18127.

[67] A. León Sandoval, K. E. Doherty, G. P. Wadey, C. M. Schroeder, N. E. Leadbeater, *Tetrahedron Lett.* **2023**, *116*, DOI 10.1016/j.tet-let.2022.154332.

[68] Y. Hu, N. Li, G. Li, A. Wang, Y. Cong, X. Wang, T. Zhang, *Green Chem.* **2017**, *19*, 1663–1667.

[69] K. Kumar, P. Joshi, D. S. Rawat, *Tetrahedron Lett.* **2021**, *81*, 153298.

[70] R. C. Simon, B. Grischek, F. Zepeck, A. Steinreiber, F. Belaj, W. Kroutil, *Angew. Chem. Int. Ed.* **2012**, *51*, 6713–6716.

[71] D. Cantillo, C. O. Kappe, *J. Org. Chem.* **2013**, *78*, 10567–10571.

[72] G. Rigoni, P. V. S. Nylund, M. Albrecht, *Dalton Trans.* **2023**, *52*, 7992–8002.

[73] S. Zhang, J. Zhang, H. Zou, *Org. Lett.* **2023**, *25*, 1850–1855.

[74] Y.-M. Yang, W. Yan, H.-W. Hu, Y. Luo, Z.-Y. Tang, Z. Luo, *J. Org. Chem.* **2021**, *86*, 12344–12353.

[75] K. P. De Jong, *Synthesis of Solid Catalysts*, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany **2009**.