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Gold(I) Complexes with Ferrocenylphosphino Sulfonate Ligands: Synthesis and Application in the Catalytic Addition of Carboxylic Acids to Internal Alkynes in Water

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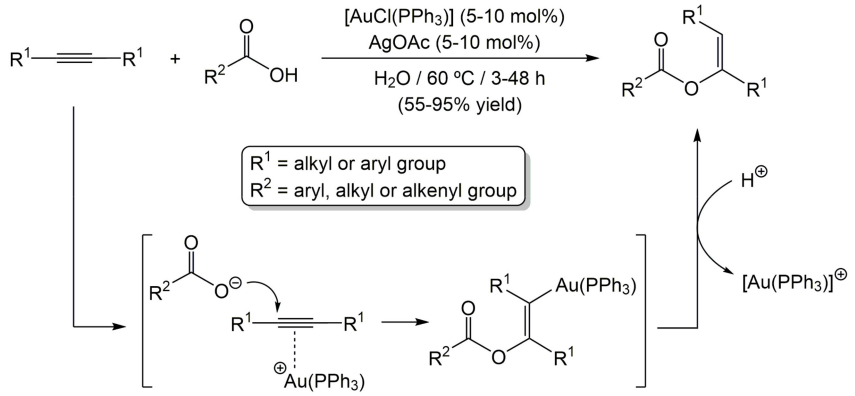
Abstract: The synthesis and characterization of novel gold(I) complexes containing hydrophilic ferrocenylphosphino sulfonate ligands, i.e., compounds [AuCl{(η^5-$C_5H_3PR_2(SO_3{}^iPr)$)Fe(η^5-C_5H_5)}] (R = Ph (**2a**), *p*-Tol (**2b**), Cy (**2c**)), are presented, including a single-crystal X-ray diffraction study on **2a**. Complexes **2a–c** were checked as catalysts for the intermolecular addition of carboxylic acids to nonactivated internal alkynes using water as a green reaction medium. The best results in terms of activity were obtained with **2a** in combination with AgOAc, which was able to promote the selective anti addition of a variety of aromatic, aliphatic, and α,β-unsaturated carboxylic acids to both symmetrical and unsymmetrical internal alkynes at 60 °C, employing metal loadings of only 2 mol %.

Keywords: ferrocenylphosphines; gold catalysts; aqueous catalysis; enol esters; hydro-oxycarbonylation reactions

1. Introduction

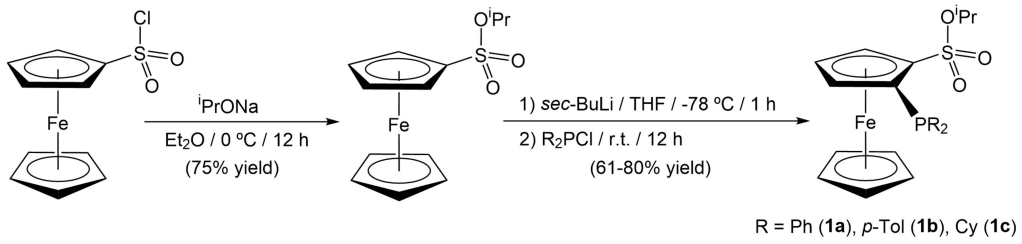
Enol esters represent an important class of synthons in organic chemistry, commonly employed as intermediates, among others, in cross-coupling [1–3], asymmetric hydrogenation [4–6], and cyclization reactions [7–9], as well as monomers in polymerization and oligomerization processes [10–12]. Among the different methods of synthesis of these valuable molecules, the intermolecular addition of carboxylic acids to alkynes catalyzed by transition metals (hydro-oxycarbonylation reaction) is probably the most straightforward and atom-economical one because the starting materials are widely available and no byproducts are generated in the process. A large number of catalytic systems, mainly involving Groups 8–11 metals, have been reported in the literature, with those based on ruthenium being probably the most popular [13–17]. However, the vast majority of studies have focused on the hydro-oxycarbonylation of terminal alkynes. Examples of the intermolecular addition of carboxylic acids to internal alkynes still remain scarce [18], and in most of the cases, only activated substrates, such as trifluoromethylated alkynes [19], acetylenic esters [20], ynol ethers [21], ynamides [22],

or iodoalkynes [23], have been considered. For nonactivated internal alkynes, only a very limited number of gold- and cobalt-based catalysts have proven effective under mild conditions (temperatures below 100 °C) [24–27]. It is also worth noting that, despite the growing interest in developing catalytic transformations in environmentally friendly aqueous media [28], efforts devoted to finding catalytic systems able to promote the hydro-oxycarbonylation of alkynes in water have been very scarce, with most of the examples dealing with intramolecular processes [29]. In fact, the only protocol for the intermolecular addition of carboxylic acids to internal alkynes in water that can be currently found in the literature was developed by our group, making use of the gold(I) complex [AuCl(PPh_3)] in combination with the chloride abstractor AgOAc [30]. As shown in Scheme 1, the trisubstituted enol ester products were generated with complete Z-stereoselectivity as the result of the anti-addition of the carboxylate anion to the corresponding cationic π-alkyne-Au(I) intermediate.



Scheme 1. Catalytic addition of carboxylic acids to internal alkynes in H_2O, employing [AuCl(PPh_3)].

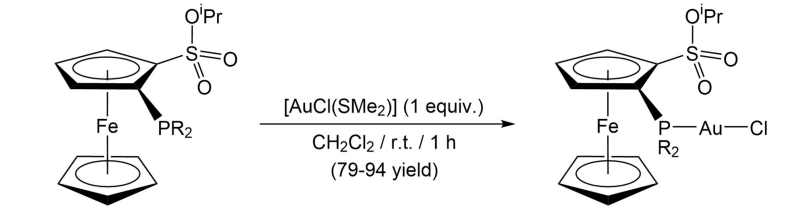
Given the tremendous effect that ligands can exert in homogeneous Au catalysis [31], we reasoned that a change in the nature of the coordinated phosphine ligand could improve these previous results. In particular, we turned our attention to the ferrocenylphosphino sulfonates **1a–c** recently synthesized by us (Scheme 2), because preliminary studies showed their utility as auxiliary *P*-donor ligands in ruthenium-catalyzed C–H activation processes in aqueous media [32]. In addition, compounds **1a–c** represent rare examples of hydrophilic ferrocenylphosphines, a particular class of ligands whose potential in aqueous catalysis remains almost unexplored. Thus, in this work, the preparation of gold(I) complexes containing the ferrocenylphosphines **1a–c** is presented, as well as an evaluation of their catalytic activity in hydro-oxycarbonylation reactions of nonactivated internal alkynes in water.



Scheme 2. Synthetic route employed for the preparation of the ferrocenyl sulfonate ligands **1a–c**.

2. Results and Discussion

The treatment of dichloromethane solutions of the ferrocenylphosphino sulfonates **1a–c** with one equivalent of [AuCl(SMe_2)] at room temperature led to the clean and fast formation of the novel gold(I) complexes **2a–c** through the expected displacement of the labile dimethylsufide ligand (Scheme 3).



Scheme 3. Synthesis of the ferrocenylphosphino sulfonate–gold(I) complexes **2a**–**c**.

The characterization of complexes **2a**–**c**, which were isolated as air-stable yellow solids in 79–94% yield, was straightforward following their analytical and spectroscopic data (details are given in Materials and Methods). In particular, the $^{31}P\{^1H\}$ NMR spectra were very informative, showing in all the cases a singlet resonance at δ_P 26.2–49.8 ppm, strongly deshielded with respect to that of the free ferrocenylphosphino sulfonates **1a**–**c** (δ_P from −22.2 to −12.0 ppm) [32]. The ^1H and $^{13}C\{^1H\}$ NMR spectra were also fully consistent with the proposed formulations, featuring two sets of signals for the R substituents of the phosphino groups, as well as for the diastereotopic methyl units of the O–^{i}Pr moieties (i.e., two doublet signals at δ_H 0.91–1.46 ppm ($^3J_{HH}$ = 6.0–6.3 Hz) and two singlets at δ_C 22.6–23.6 ppm), as a consequence of the planar chirality of the ferrocenyl fragments due to the 1,2-disubstitution of one of their Cp rings. In addition, the structure of complex **2a** was unambiguously confirmed by means of a single-crystal X-ray diffraction study. X-ray quality crystals were obtained by slow diffusion of hexane into a saturated solution of **2a** in dichloromethane. An ORTEP-type view of the molecule, along with selected structural parameters, is shown in Figure 1.

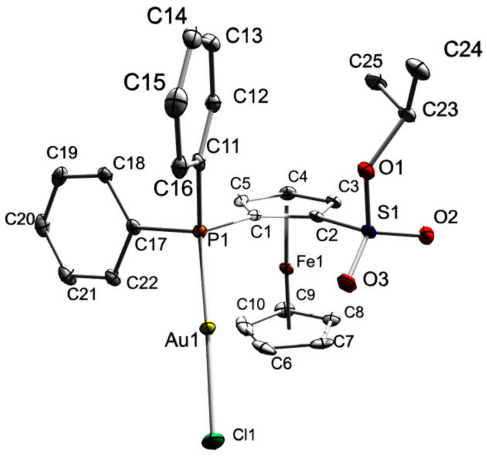


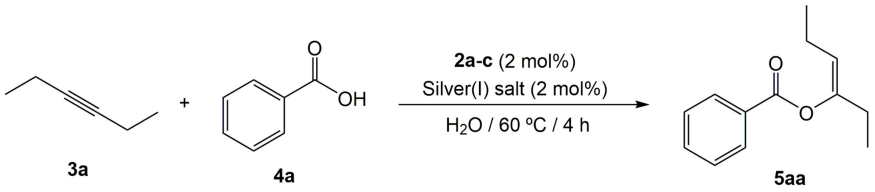
Figure 1. ORTEP-type view of the structure of complex **2a** showing the crystallographic labelling scheme. Hydrogen atoms have been omitted for clarity. Thermal ellipsoids are drawn at the 30% probability level. Selected bond distances (Å) and angles (deg): Fe(1)–C* = 1.6300(5); Fe(1)–C** = 1.6545(5); Au(1)–Cl(1) = 2.2893(9); Au(1)–P(1) = 2.2340(9); P(1)–C(1) = 1.805(4); P(1)–C(11) = 1.823(4); P(1)–C(17) = 1.808(4); S(1)–C(2) = 1.741(4); S(1)–O(1) = 1.570(2); S(1)–O(2) = 1.426(3); S(1)–O(3) = 1.429(3); O(1)–C(23) = 1.486(4); C*–Fe–C** = 175.67(4); P(1)–Au(1)–Cl(1) = 175.72(3); Au(1)–P(1)–C(1) = 115.6(1); Au(1)–P(1)–C(11) = 115.1(1); Au(1)–P(1)–C(11) = 110.2(1); C(1)–P(1)–C(11) = 105.5(2); C(1)–P(1)–C(17) = 102.8(2); C(11)–P(1)–C(17) = 106.5(2); C(2)–S(1)–O(1) = 103.4(2); C(2)–S(1)–O(2) = 108.3(2); C(2)–S(1)–O(3) = 109.3(2); O(1)–S(1)–O(2) = 110.8(2); O(1)–S(1)–O(3) = 104.2(2); O(2)–S(1)–O(3) = 119.8(2); S(1)–O(1)–C(23) = 120.4(2); C* and C** denote the centroids of the cyclopentadienyl rings (C(1), C(2), C(3), C(4), and C(5), and C(6), C(7), C(8), C(9), and C(10), respectively).

The coordination around the gold atom is almost linear with a P(1)–Au(1)–Cl(1) angle of 175.72(3)°, and bond distances Au(1)–P(1) and Au(1)–Cl(1) of 2.2340(9) and

2.2893(9) Å, respectively. These bonding parameters compare well with those previously found in the solid-state crystal structures of related ferrocenylphosphine–gold(I) complexes, like [Au_2Cl_2(μ-dppf)] (dppf = 1,1´-bis(diphenylphosphino)ferrocene; Au–P = 2.2262(13) Å, Au–Cl = 2.2815(13) Å, and P–Au–Cl = 179.59(5)°) [33], [Au_2Cl_2\{μ-(η^5-1,3-$C_5H_3PPh_2$(OSi^iPr_3))$_2$Fe\}] (Au–P = 2.2282(9) Å, Au–Cl = 2.2814(10) Å, and P–Au–Cl = 177.35(4)°) [34] or [AuCl\{(η^5-1,2-$C_5H_3PPh_2$(1-naphthyl))Fe(η^5-C_5H_5)\}] (Au–P = 2.2278(11) Å, Au–Cl = 2.2845(11) Å, and P–Au–Cl = 174.16(5)°) [35]. On the other hand, the observed bond distances within the ferrocenylphosphine sulfonate skeleton were very similar to those found in the structure of the free ligand **1a** (± 0.04 Å) [32]. The same can be said about the bond angles, where the most noticeable differences were the increase in ca. 5–6° of the C(1)–P(1)–C(11) and C(1)–P(1)–C(17) angles when passing from **1a** to **2a**. All these observations indicate a negligible influence of the gold coordination on the geometry of the ligand.

With the complexes [AuCl\{(η^5-$C_5H_3PR_2$($SO_3{}^iPr$))Fe(η^5-C_5H_5)\}] (**2a–c**) in hand, we next explored their catalytic potential in hydro-oxycarbonylation reactions of internal alkynes in water. In particular, a first set of experiments was performed with complex **2a** and the model substrates hex-3-yne (**3a**) and benzoic acid (**4a**) (see Table 1).

Table 1. Addition of benzoic acid (**4a**) to hex-3-yne (**3a**) catalyzed by complexes **2a–c** in water.[1].



3a **4a** **5aa**

Entry	Catalyst	Silver Salt	Yield (%)[2]
1	[AuCl\{(η^5-$C_5H_3PPh_2$($SO_3{}^iPr$))Fe(η^5-C_5H_5)\}] (**2a**)	—	0
2	[AuCl\{(η^5-$C_5H_3PPh_2$($SO_3{}^iPr$))Fe(η^5-C_5H_5)\}] (**2a**)	$AgPF_6$	79
3	[AuCl\{(η^5-$C_5H_3PPh_2$($SO_3{}^iPr$))Fe(η^5-C_5H_5)\}] (**2a**)	$AgSbF_6$	49
4	[AuCl\{(η^5-$C_5H_3PPh_2$($SO_3{}^iPr$))Fe(η^5-C_5H_5)\}] (**2a**)	$AgNO_3$	87
5	[AuCl\{(η^5-$C_5H_3PPh_2$($SO_3{}^iPr$))Fe(η^5-C_5H_5)\}] (**2a**)	AgOTs	86
6	[AuCl\{(η^5-$C_5H_3PPh_2$($SO_3{}^iPr$))Fe(η^5-C_5H_5)\}] (**2a**)	AgOTf	82
7	[AuCl\{(η^5-$C_5H_3PPh_2$($SO_3{}^iPr$))Fe(η^5-C_5H_5)\}] (**2a**)	AgOAc	91 (87)[3]
8	[AuCl\{(η^5-C_5H_3P(*p*-Tol)$_2$($SO_3{}^iPr$))Fe(η^5-C_5H_5)\}] (**2b**)	AgOAc	89
9	[AuCl\{(η^5-$C_5H_3PCy_2$($SO_3{}^iPr$))Fe(η^5-C_5H_5)\}] (**2c**)	AgOAc	77
10	———	AgOAc	4

[1] All the reactions were performed under Ar atmosphere at 60 °C using 1.2 mmol of hex-3-yne (**3a**), 1.0 mmol of benzoic acid (**4a**), and 3 mL of water. [2] Yields of **5aa** determined by gas chromatography (GC). [3] Isolated yield after work-up in brackets.

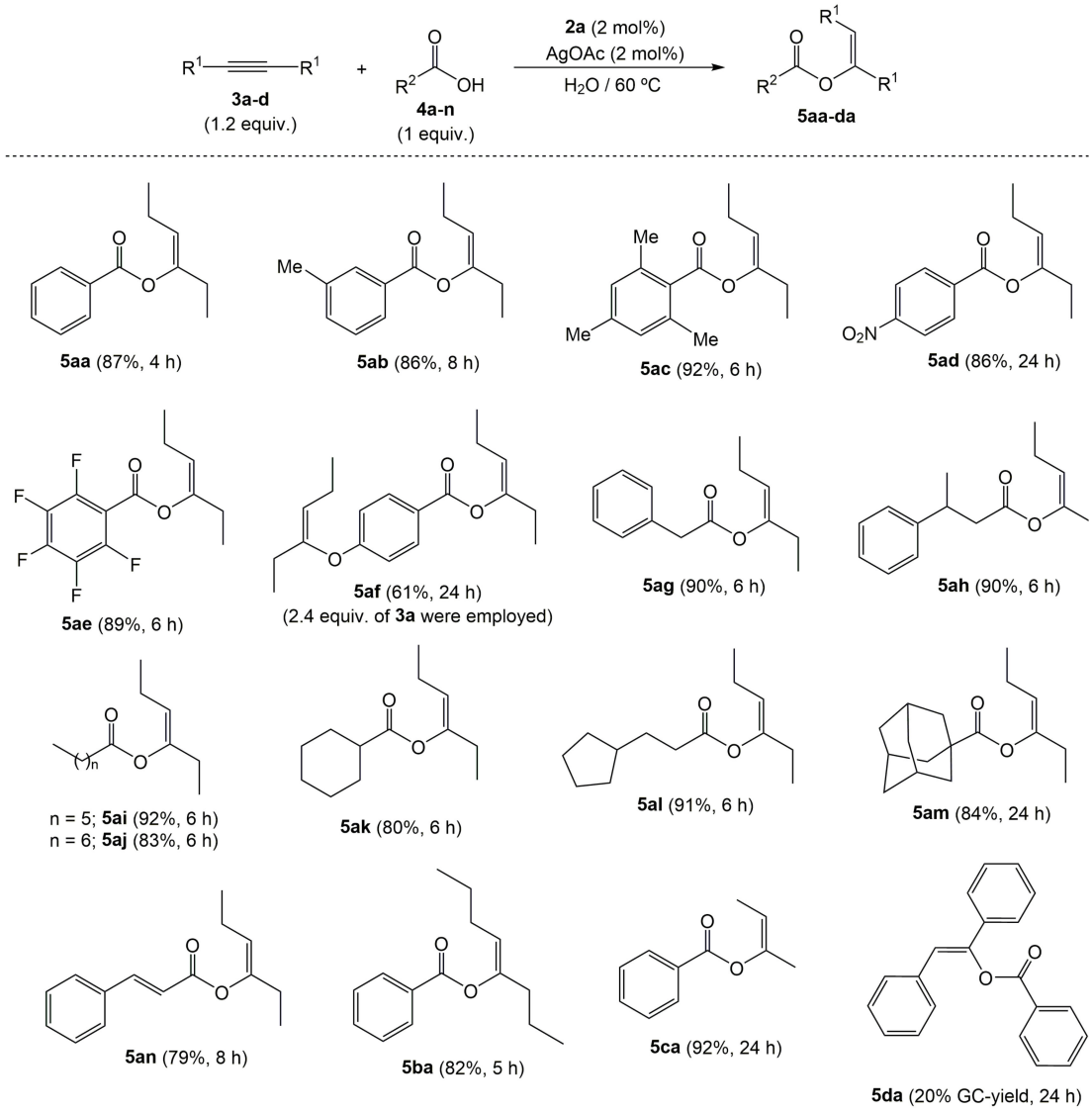
As shown in entry 1, when a mixture of **3a** (1.2 mmol), **4a** (1 mmol), and complex **2a** (0.02 mmol; 2 mol %) in water (3 mL) was heated at 60 °C for 4 h, no reaction was observed, suggesting the need for a halide extractor to generate the catalytically active cationic gold(I) species. In this regard, different silver(I) salts (2 mol%) were screened (entries 2–7), obtaining positive results in all cases. In particular, the best result was achieved with AgOAc, which led to the desired enol ester **5aa** in 91% gas chromatography (GC) yield after 4 h of heating (entry 7). Work-up of the reaction mixture allowed for isolation of pure **5aa** in 87% yield (see details in Materials and Methods). Employing the same reaction conditions, the catalytic performance of the bis(*p*-tolyl)phosphino complex **2b** was found to be very similar to that shown by complex **2a** (entries 8 vs. 7). The dicyclohexylphosphino complex **2c** proved to also be active in the addition process, but its effectiveness was slightly lower in comparison to that of **2a** and **2b** (entry 9 vs. 7 and 8). Although steric effects cannot be discarded, the lower reactivity of **2c** is most probably related to the higher electronic density of the metal center, which reduces the electrophilic character of the corresponding gold cation disfavoring the coordination of the alkyne substrate. Also of note is the fact that, as previously observed employing the catalytic

system [AuCl(PPh_3)]/AgOAc (see Scheme 1) [30], all the reactions collected in Table 1 proceeded cleanly without any side-reaction associated with the hydration of the C≡C bond or oligomerization processes, and with an exquisite anti selectivity (only the *Z* isomer of **5aa** is formed). A blank experiment with AgOAc alone confirmed that gold is responsible for the catalytic activity observed (entry 10). We would also like to highlight in this point that the effectiveness shown by the **2a**/AgOAc system in this reaction compares favorably with that reported for [AuCl(PPh_3)]/AgOAc (5 mol % of both reagents were needed to generate **5aa** in a comparable yield under identical experimental conditions) [30], which could be explained in terms of the higher solubility in the water of complex **2a** (ca. 10 mg/mL at 60 °C). However, the different reactivities observed between complexes **2a**, **2b**, and **2c** do not seem to be related to their water solubilities, since the most soluble one **2c** (ca. 13 mg/mL at 60 °C) is the least effective (the solubility of **2b** is identical to that of **2a**).

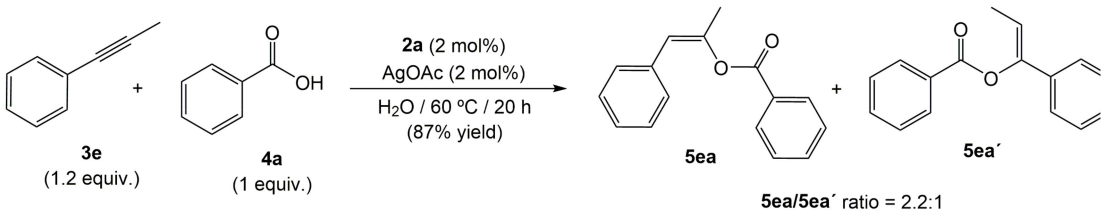
The scope of Au(I) complex **2a** was subsequently explored by varying firstly the carboxylic acid reagent. Thus, as shown in Scheme 4, different benzoic acids **4b–f** could be successfully added to hex-3-yne (**3a**), regardless of the electronic nature and substitution pattern of the aryl ring. As for **5aa**, the resulting enol esters **5ab–af** were exclusively obtained as the corresponding *Z* isomers, as assessed by comparison of their NMR data with literature values [30]. The use of 4-hydroxybenzoic acid (**4f**) led to an interesting result because, in addition to the expected hydro-oxycarbonylation reaction, the hydroalkoxylation of **3a** also occurred, leading to the previously unknown enol ester **5af** (to obtain this compound in good yield, a **3a/4f** ratio of 2.4:1 was employed). We would like to remark here that, although gold-catalyzed intermolecular hydroalkoxylation reactions of alkynes have been extensively studied [36], no previous examples in water can be found in the literature. As exemplified with compounds **5ag–an**, the addition process could also be extended to benzylic, homobenzylic, aliphatic, and α,β-unsaturated carboxylic acids, thus confirming the wide scope of **2a** towards the carboxylate partner (Scheme 2). The enol esters **5ab–an** were isolated, after extraction of the reaction mixture with diethyl ether and subsequent chromatographic purification, in 61–92% yield (conversions ≥ 85% were in all cases observed by GC), with reaction times ranging from 5 to 24 h.

Additional studies varying the nature of the alkyne were also performed. Thus, as observed for hex-3-yne (**3a**), the addition of benzoic acid to oct-4-yne (**3b**) and but-2-yne (**3c**) also proceeded cleanly under the standard conditions, leading to the corresponding enol esters **5ba** and **5ca**, which were isolated in 82–92% yield (see Scheme 4). In contrast, a very poor result was obtained when diphenylacetylene (**3d**) was employed as substrate, the reaction leading to a maximum 20% GC yield of the desired enol ester product **5da** after 24 h (Scheme 4). The higher steric constraints of this particular alkyne could be behind this negative result.

To complete the study, the catalytic addition of benzoic acid (**4a**) to a nonsymmetrically substituted alkyne, i.e., 1-phenyl-1-propyne (**3e**), was finally explored. As shown in Scheme 5, the reaction proceeded in high yield after 20 h, but with a relatively low regioselectivity. Thus, a nonseparable mixture of the regioisomeric enol esters **5ea** and **5ea´** was formed in ca. 2.2:1 ratio.



Scheme 4. Addition of different carboxylic acids to symmetrically substituted internal alkynes (isolated yields are given).



Scheme 5. Addition of benzoic acid to 1-phenyl-1-propyne catalyzed by the gold(I) complex **2a**.

3. Materials and Methods

All the synthetic procedures described in this article were performed under inert atmosphere (dry argon) using vacuum-line and Schlenk or sealed-tube techniques. Organic solvents were purified by standard methods and distilled under inert atmosphere before use [37]. All reagents employed in this work were obtained from commercial suppliers and used as received, with the exception of the ferrocenylphosphino sulfonate ligands (η^5-$C_5H_3PR_2(SO_3{}^iPr)$)Fe(η^5-C_5H_5) (**1a–c**) [32] and the gold(I) complex [AuCl(SMe_2)] [38], which were synthesized as previously described in the literature. NMR spectra were recorded at room temperature making use of Bruker DPX-300 or AV400 instruments

(Billerica, MA, USA). The residual signal of the deuterated solvent was employed as reference for $^{13}C\{^1H\}$ and ^1H NMR chemical shifts, while 85% H_3PO_4 was used as an external standard for the $^{31}P\{^1H\}$ NMR measurements. DEPT experiments were systematically performed for all the compounds synthesized. A PerkinElmer 1720-XFT spectrometer (Waltham, MA, USA) and a Hewlett Packard HP6890 apparatus (Supelco Beta-Dex^{TM} 120 column, 30 m length, 250 μm diameter, (Palo Alto, CA, USA) were employed for IR and GC measurements, respectively. Elemental analyses and HRMS data (QTOF Bruker Impact II mass spectrometer) were provided by the Analytical Service of the Instituto de Investigaciones Químicas (IIQ-CSIC) of Seville and the General Services of the University of Oviedo, respectively. Merck silica gel 60 (230–400 mesh) was employed for the chromatographic work-ups.

3.1. General Procedure for the Preparation of Complexes [AuCl{(η^5-$C_5H_3PR_2(SO_3{}^iPr)$)Fe(η^5-C_5H_5)}] (R = Ph (2a), p-Tol (2b), Cy (2c))

In a Schlenk flask filled with Ar and equipped with a stir bar, the corresponding ferrocenylphosphino sulfonate ligand **1a**–**c** (0.40 mmol) was dissolved in 10 mL of dichloromethane. Then, 0.40 mmol (0.119 g) of [AuCl(SMe_2)] was added to the resulting solution, and the mixture was stirred at room temperature for 1 h (a color change from orange-red to yellow was observed). After this time, the solvent was removed under vacuum, and the yellow solid obtained recrystallized from a 1:1 v/v dichloromethane/hexane mixture (ca. 20 mL), washed with hexane (ca. 10 mL), and dried in vacuo. Characterization data for the resulting Au(I) complexes **2a**–**c** are as follows:

3.1.1. [AuCl{(η^5-$C_5H_3PPh_2(SO_3{}^iPr)$)Fe(η^5-C_5H_5)}] (2a)

Yield: 0.235 g (81%). $^{31}P\{^1H\}$ NMR (121 MHz, $CDCl_3$): δ = 27.7 (s) ppm. ^1H NMR (300 MHz, $CDCl_3$): δ = 7.76–7.69 (m, 2H, Ph), 7.58–7.45 (m, 8H, Ph), 5.17 and 3.87 (s, 1H each, CH of C_5H_3), 4.73 (sept, 1H, $^3J_{HH}$ = 6.3 Hz, C*H*Me_2), 4.63 (s, 6H, C_5H_5 and CH of C_5H_3), 1.14 and 0.91 (d, 3H each, $^3J_{HH}$ = 6.3 Hz, CH*Me*$_2$) ppm. $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ = 134.6 and 133. 9 (d, J_{PC} = 14.7 Hz, CH_{ortho} or CH_{meta} of Ph), 132.1 and 131.8 (d, J_{PC} = 2.2 Hz, CH_{para} of Ph), 129.7 (d, J_{PC} = 61.1 Hz, C_{ipso} of Ph), 129.5 (d, J_{PC} = 62.0 Hz, C_{ipso} of Ph), 129.0 (d, J_{PC} = 12.0 Hz, CH_{ortho} or CH_{meta} of Ph), 128.8 (d, J_{PC} = 12.2 Hz, CH_{ortho} or CH_{meta} of Ph), 88.9 (d, J_{PC} = 12.0 Hz, C of C_5H_3), 77.3 (d, J_{PC} = 5.7 Hz, CH of C_5H_3), 76.5 (s, *C*HMe_2), 75.9 (d, J_{PC} = 4.6 Hz, CH of C_5H_3), 73.5 (s, C_5H_5), 72.0 (d, J_{PC} = 6.9 Hz, CH of C_5H_3), 71.2 (d, J_{PC} = 66.2 Hz, C of C_5H_3), 23.0 and 22.7 (s, CH*Me*$_2$) ppm. IR (KBr): ν = 3107 (w), 2981 (w), 2933 (w), 1436 (m), 1330 (s), 1207 (m), 1166 (s), 1151 (m), 1096 (m), 1037 (w), 961 (w), 901 (m), 868 (s), 838 (m), 750 (m), 693 (m), 659 (s), 599 (m), 481 (m) cm^{-1}. Elemental analysis calcd. (%) for $C_{25}H_{25}O_3AuClFePS$: C 41.43, H 3.48; found: C 41.47, H 3.47.

3.1.2. [AuCl{(η^5-$C_5H_3P(p\text{-Tol})_2(SO_3{}^iPr)$)Fe($\eta^5$-$C_5H_5$)}] (2b)

Yield: 0.238 g (79%). $^{31}P\{^1H\}$ NMR (121 MHz, $CDCl_3$): δ= 26.2 (s) ppm. ^1H NMR (300 MHz, $CDCl_3$): δ= 7.64–7.57 (m, 2H, C_6H_4Me), 7.45–7.38 (m, 2H, C_6H_4Me), 7.31–7.22 (m, 4H, C_6H_4Me), 5.15 and 3.88 (s, 1H each, CH of C_5H_3), 4.71 (sept, 1H, $^3J_{HH}$ = 6.0 Hz, C*H*Me_2), 4.62 (s, 6H, C_5H_5 and CH of C_5H_3), 2.44 and 2.40 (s, 3H each, C_6H_4*Me*), 1.15 and 0.93 (d, 3H each, $^3J_{HH}$ = 6.0 Hz, CH*Me*$_2$) ppm. $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ= 142.6 and 142.3 (s, C_{para} of C_6H_4Me), 134.5 and 133. 9 (d, J_{PC} = 15.1 Hz, CH_{ortho} or CH_{meta} of C_6H_4Me), 129.7 and 129.5 (d, J_{PC} = 12.3 Hz, CH_{ortho} or CH_{meta} of C_6H_4Me), 126.5 and 126.3 (d, J_{PC} = 63.8 Hz, C_{ipso} of C_6H_4Me), 88.7 (d, J_{PC} = 1.9 Hz, C of C_5H_3), 77.3 (d, J_{PC} = 6.0 Hz, CH of C_5H_3), 76.5 (s, *C*HMe_2), 75.8 (d, J_{PC} = 4.5 Hz, CH of C_5H_3), 73.4 (s, C_5H_5), 71.7 (d, J_{PC} = 6.9 Hz, CH of C_5H_3), 72.0 (d, J_{PC} = 65.9 Hz, C of C_5H_3), 23.0 and 22.6 (s, CH*Me*$_2$), 21.5 and 21.4 (s, C_6H_4*Me*) ppm. IR (KBr): ν= 2978 (w), 2924 (w), 1597 (w), 1497 (w), 1368 (m), 1357 (m), 1331 (m), 1202 (m), 1166 (s), 1100 (s), 1035 (w), 960 (w), 916 (s), 881 (m), 833 (w), 806 (m), 754 (w), 627 (m), 507 (m), 495 (m) cm^{-1}. Elemental analysis calcd. (%) for $C_{27}H_{29}O_3AuClFePS$: C 43.08, H 3.88; found: C 43.15, H 3.84.

3.1.3. [AuCl{(η^5-$C_5H_3PCy_2(SO_3{}^iPr)$)Fe(η^5-C_5H_5)}] (2c)

Yield: 0.277 g (94%). $^{31}P\{^1H\}$ NMR (121 MHz, $CDCl_3$): δ = 49.8 (s) ppm. ^1H NMR (300 MHz, $CDCl_3$): δ = 5.09, 4.90 and 4.76 (s, 1H each, CH of C_5H_3), 5.02 (sept, 1H, $^3J_{HH}$ = 6.0 Hz, C*H*Me$_2$), 4.57 (s, 5H, C_5H_5), 2.91–2.78 and 2.61–2.55 (m, 1H each, CH of Cy), 2.07,1.65 (m, 12H, CH_2 of Cy), 1.48–1.12 (m, 8H, CH_2 of Cy), 1.46 and 1.32 (d, 3H each, $^3J_{HH}$ = 6.0 Hz, CH*Me*$_2$) ppm. $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ = 87.0 (d, J_{PC} = 3.1 Hz, C of C_5H_3), 81.5 (d, J_{PC} = 17.6 Hz, CH of C_5H_3), 77.2 (s, CHMe$_2$), 75.3 (d, J_{PC} = 3.0 Hz, CH of C_5H_3), 73.2 (s, C_5H_5), 72.1 (d, J_{PC} = 9.5 Hz, CH of C_5H_3), 69.4 (d, J_{PC} = 49.8 Hz, C of C_5H_3), 35.7 (d, J_{PC} = 33.2 Hz, CH of Cy), 35.2 (d, J_{PC} = 33.9 Hz, CH of Cy), 33.5 (d, J_{PC} = 3.9 Hz, CH_2 of Cy), 31.4 (d, J_{PC} = 2.6 Hz, CH_2 of Cy), 29.2, 28.6, 25.7 and 25.6 (s, CH_2 of Cy), 26.7 (d, J_{PC} = 13.6 Hz, CH_2 of Cy), 26.6 (d, 2C, J_{PC} = 6.9 Hz, CH_2 of Cy), 26.5 (d, J_{PC} = 13.2 Hz, CH_2 of Cy), 23.6 and 22.9 (s, CH*Me*$_2$) ppm. IR (KBr): ν = 2928 (s), 2852 (m), 1449 (w), 1369 (s), 1334 (m), 1204 (m), 1167 (s), 1093 (w), 1047 (w), 1003 (w), 905 (s), 876 (s), 837 (m), 756 (m), 628 (s), 508 (m), 483 (w) cm^{-1}. Elemental analysis calcd. (%) for $C_{25}H_{37}O_3AuClFePS$: C 40.75, H 5.06; found: C 40.80, H 5.10.

3.2. General Procedure for the Addition of Carboxylic Acids to Internal Alkynes Catalyzed by Complex 2a

Under an argon atmosphere, the corresponding internal alkyne **3a–e** (1.2 mmol) and carboxylic acid **4a–n** (1 mmol), the gold complex [AuCl{(η^5–$C_5H_3PPh_2(SO_3{}^iPr)$)Fe(η^5–C_5H_5)}] (**2a**) (0.014 g; 0.02 mmol), AgOAc (0.003 g; 0.02 mmol), and water (3.0 mL) were introduced into a Teflon-capped sealed tube, and the reaction mixture was stirred at 60 °C for the indicated time (see Schemes 4 and 5). The course of the reaction was monitored regularly, taking samples of ca. 5 μL, which, after extraction with CH_2Cl_2, were analyzed by GC. Once the reaction finished, the mixture was extracted with diethyl ether (3 x 5 mL), and the organic phase was dried over $MgSO_4$ and evaporated to dryness. The resulting oily residue was purified by flash column chromatography over silica gel using diethyl ether/hexane (1:10) as eluent. The identity of the enol ester products was assessed by comparison of their NMR spectroscopic data with those previously reported by us [30] or, in the case of **5ag**, by Tsukada and coworkers [39]. Copies of the NMR spectra are included in the Supplementary Materials.

3.3. Synthesis and Characterization of (Z)-Hex-3-en-3-yl 4-(((Z)-Hex-3-en-3-yl)oxy)benzoate 5af

The novel enol ester **5af**, isolated as a colourless oil after 24 h of heating, was obtained following the general procedure detailed in Section 3.2, starting from hex-3-yne (**3a**; 0.273 mL; 2.4 mmol) and 4-hydroxybenzoic acid (**4f**; 0.138 g; 1 mmol). Yield: 0.184 g (61%). ^1H NMR (300 MHz, $CDCl_3$): δ = 8.09–8.06 (m, 2H, CH_{arom}), 7.00–6.98 (m, 2H, CH_{arom}), 5.11 (m, 2H, =CH), 2.33–2.28 (m, 2H, CH_2), 2.20–2.16 (m, 2H, CH_2), 2.02–1.96 (m, 4H, CH_2), 1.12–1.08 (m, 6H, CH_3), 1.06–0.93 (m, 6H, CH_3) ppm. $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): δ = 164.2 (s, C=O), 161.2 and 122.7 (s, C_{arom}), 151.1 and 149.5 (s, =C), 132.1 and 115.2 (s, CH_{arom}), 117.5 and 117.0 (s, =CH), 26.6, 25.6, 18.8, and 18.6 (s, CH_2), 13.9, 13.8, 11.4, and 11.3 (s, CH_3) ppm. IR (neat): ν = 2968 (m), 2912 (m), 2875 (m), 1729 (s), 1691 (m), 1604 (s), 1504 (s), 1462 (m), 1418 (w), 1376 (w), 1263 (s), 1237 (s), 1181 (m), 1086 (s), 1022 (w), 972 (w), 850 (m), 746 (m) cm^{-1}. HRMS (ESI): *m/z* 325.1763, [M + Na^+] (calcd. for $C_{19}H_{26}O_3Na$: 325.1774).

3.4. X-ray Crystal Structure Determination of Compound 2a

Crystals suitable for X-ray diffraction analysis were obtained by slow diffusion of hexane into a saturated solution of compound **2a** in dichloromethane. The most relevant crystal and refinement data are collected in Table 2. Diffraction data were recorded on an Oxford Diffraction Xcalibur Nova single-crystal diffractometer, using Cu-Kα radiation (λ = 1.5418 Å), with a crystal-to-detector distance fixed at 62 mm and using the oscillation method, with 1° oscillation and variable exposure time per frame of 2.5–6.5 s. The data collection strategy was calculated with the program CrysAlis Pro CCD [40]. Data reduction and cell refinement were performed with the program CrysAlis Pro RED [40]. Empirical absorption correction was applied by means of a SCALE3 ABSPACK algorithm as implemented in the program CrysAlis Pro RED [40]. The software package WINGX was used for space group

determination, structure solution, and refinement [41]. The structure was solved by direct methods using SHELXL97 [42]. Isotropic least-squares refinement on F^2 using SHELXL97 was performed [42]. During the final stages of the refinement, all the positional parameters and the anisotropic temperature factors of all the non-H atoms were refined. The coordinates of the H atoms were found from different Fourier maps and included in the refinement with isotropic parameters. The function minimized was $[\Sigma w(F_o^2 - F_c^2)/\Sigma w(F_o^2)]^{1/3}$ where $w = 1/[\sigma^2(F_o^2) + (0.0457P)^2 + 0.2366P]$ with $\sigma(F_o^2)$ from counting statistics and $P = (\text{Max}(F_o^2,0) + 2F_c^2)/3$. Atomic scattering factors were taken from the International Tables for X-ray Crystallography [43]. Geometrical calculations were made with PARST [44]. The crystallographic plots were made with DIAMOND [45]. Supplementary crystallographic data for the structural analysis have been deposited with the Cambridge Crystallographic Data Centre, CCDC-1961685.

Table 2. Crystal data and structure refinement details for compound **2a**.

Chemical Formula	**$C_{25}H_{25}O_3AuClFePS$**
fw	724.74
T (K)	130(1)
cryst. syst.	monoclinic
space group	P 2_1/n
cryst. size mm^3	0.24 x 0.10 x 0.07
a, Å	10.15090(10)
b, Å	14.6795(2)
c, Å	16.9056(2)
α, deg	90
β, deg	101.7130(10)
γ, deg	90
Z	4
V, $Å^3$	2466.65(5)
ρ_{calcd}, g cm^{-3}	1.952
μ, mm^{-1}	18.351
F(000)	1408
θ range, deg	3.0104 to 69.6789
index ranges	$-10 \le h \le 12$; $-16 \le k \le 17$; $-20 \le l \le 18$
completeness to θ_{max}	98%
no. of data collected	12340
no. of unique data	4556
no. of parameters/restrains	332/0
refinement method	full-matrix least-squares on F^2
goodness of fit on F^2	1.082
R1[a] [I > 2σ(I)]	0.0271
wR2[a] [I > 2σ(I)]	0.0723
R1 (all data)	0.0292
wR2 (all data)	0.0741

[a] $R1 = \sum(|F_o| - |F_c|)/\sum|F_o|$; $wR2 = \{\sum[w(F_o^2 - F_c^2)\sum]/\sum[w(F_o^2)^2]\}^{\frac{1}{2}}$.

4. Conclusions

In summary, new gold(I) complexes featuring hydrophilic ferrocenylphophino sulfonate ligands were synthesized, i.e., compounds [AuCl{(η^5-$C_5H_3PR_2(SO_3{}^iPr)$)Fe(η^5-C_5H_5)}] (R = Ph (**2a**), *p*-Tol (**2b**), Cy (**2c**)), and evaluated as potential catalysts for hydro-oxycarbonylation reactions of nonactivated internal alkynes in water. In combination with AgOAc, all of them became active, delivering the corresponding enol ester products with complete Z-selectivity. Employing **2a**/AgOAc, whose activity was found to be superior to that of the previously reported [AuCl(PPh_3)]/AgOAc system, the scope of the process could also be demonstrated. The work presented herein provides additional evidence of the utility of ferrocenylphophino sulfonates (η^5-$C_5H_3PR_2(SO_3{}^iPr)$)Fe(η^5-C_5H_5) (**1a-c**) as auxiliary ligands for metal-catalyzed organic reactions in environmentally friendly aqueous media.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4344/9/11/955/s1, Figures S1–S9: NMR spectra of the gold(I) complexes **2a–c**, and Figures S10–S44: NMR spectra of the enol esters **5aa–ea**.

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