

Carbon dioxide effect on palladium-catalyzed sequential reactions with carbon monoxide, acetylenic compounds and water

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Abstract

The effect of CO₂ on the reaction of a terminal alkyne with CO and H₂O in the presence of PdI₂–KI was studied. With simple 1-alkynes such as alkyl- or arylacetylenes in the absence of added CO₂ a catalytic process takes place with formation of substituted furan-2(5*H*)-ones **1**, deriving from a reductive carbonylation process. Oxidation of CO to CO₂ accounts for the stoichiometry of the reaction. The latter may occur through decarboxylation of a Pd–CO₂H species with formation of a Pd–H species, which is in turn responsible for the reduction process. It has been found that working in the presence of added CO₂ the latter can also work as hydrogen acceptor, probably via its insertion into the Pd–H bond. In this way a catalytic synthesis of maleic anhydrides **2**, corresponding to an oxidative carbonylation process, can be obtained even in the absence of external oxidants.

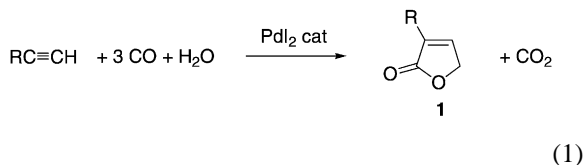
In contrast with simple 1-alkynes, the use of 2-methylbut-3-yn-2-ol in the absence of added CO₂ results in additive carbonylation with formation of teraconic anhydride **5**, formally deriving from the combination of oxidative dicarbonylation and reduction. No CO₂ effect is observed in this case, which rules out the intervention of Pd–H species in the catalytic cycle leading to **5**. As expected, however, carbon dioxide effect is felt by secondary products resulting from reductive carbonylation, their formation being curtailed by CO₂ addition to the reaction mixture.

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1. Introduction

We recently developed a new Pd-catalyzed reductive carbonylation reaction of 1-alkynes leading to furan-2(5*H*)-ones in fair yields according to Eq. (1) [1].



The reductive process occurs in conjunction with the oxidation of CO to CO₂ in the presence of water.

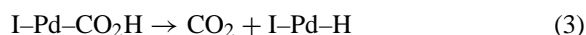
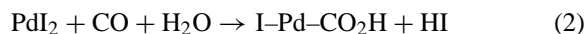
Analogously to what has been shown to occur in dimethoxycarbonylation [2,3], we postulated the intermediacy of a hydroxycarbonylpalladium species.

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Although hydroxycarbonylpalladium complexes have not been isolated, their alkoxycarbonyl analogues are well known [4] and have been shown to be able to attack triple bonds [5–7]. When it comes to the carboxylic group, however, a more complex chemistry takes place, apparently because of the tendency of the hydroxycarbonylpalladium complexes to evolve carbon dioxide, giving rise to palladium hydrides, as shown by the behavior of the parent platinum complexes [8–11]. Since analogously to other metallacarboxylic acids [9] the palladacarboxylic ones should be readily formed from palladium halides, carbon monoxide and water, the overall process, in the absence of other hydride acceptors such as the alkynes, amounts to catalytic water gas conversion [Eqs. (2)–(4); here and throughout the paper the I–Pd–CO₂H species, where CO and I[−] are present as ligands, is assumed to predominate over Pd(CO₂H)₂, containing the same ligands].



These observations prompted us to acquire further knowledge of the effect of carbon dioxide on the hydroxycarbonylation process. A short preliminary report has been published [12].

2. Experimental

2.1. General

Melting points were determined on a Reichert Thermovar melting point apparatus and are uncorrected. Elemental analyses were carried out with a Carlo Erba Elemental Analyzer Mod. 1106. ¹H NMR and ¹³C NMR spectra were taken, unless otherwise noted, in CDCl₃ solutions on a Bruker AC300 spectrometer with Me₄Si as internal standard and recorded at 300 and 75 MHz, respectively. Chemical shifts and coupling constants (*J*) are given in ppm (δ) and in Hz, respectively. IR spectra were taken on a Perkin-Elmer Paragon 1000 PC FT-IR spectrometer. Mass spectra were obtained using an HP 5972A GC-MS apparatus at 70 eV ionization voltage. All reactions were analyzed by TLC on silica gel 60 F₂₅₄ or by GLC using a

Shimadzu GC-14A gas chromatograph and capillary columns with polymethylsilicone+5% phenylsilicone as the stationary phase (HP-5). Column chromatography was performed on silica gel 60 (Merck, 70–230 mesh).

2.2. Preparation of substrates

Starting acetylenic substrates were commercially available and were used without further purification. 1,4-Dioxane was distilled from sodium/benzophenone. 5-Hydroxy-3-phenyl-2(5*H*)-furanone was prepared as described in [13]. 2(1-Hydroxy-1-methylethyl)maleic anhydride was prepared from 3-methyl-1-butyn-3-ol: a 600 ml stainless steel autoclave was charged in the presence of air with PdI₂ (27 mg, 0.075 mmol), KI (128 mg, 0.771 mmol) and a solution of alkynol (3.2 g, 38 mmol) in MeOH (175 ml). The autoclave was pressurized with CO (1.5 MPa) and air (up to 2.0 MPa) then heated at 80 °C for 3 h under stirring. After cooling the autoclave was degassed, the solvent was evaporated under reduced pressure and the residue dissolved in Et₂O was filtered on a short SiO₂ column to eliminate the catalyst and the oligomeric products. After evaporating the solvent the products were added with a 30% NaOH solution (35 ml, 262 mmol) and refluxed for 15 h. The resulting mixture was cooled, cautiously acidified with concentrated HCl, and extracted with Et₂O several times. After drying over Na₂SO₄, the solvent was eliminated by rotary evaporation and product purified by bulb-to-bulb distillation (140–145 °C, 25–13 Pa): colorless oil, 0.8 g, 4.35 mmol, 11% on the starting alkynol. IR (neat) ν (cm^{−1}): 3521 (m, br), 3119 (w), 2985 (m), 1841 (s), 1769 (s), 1634 (w), 1457 (w), 1367 (m), 1295 (m), 1243 (m), 1174 (m), 1093 (w), 899 (m). ¹H NMR δ : 6.83 (s, 1H, =CH), 1.61 (s, 6H, 2Me). ¹³C NMR δ : 164.4, 163.2, 158.7, 127.8, 69.8, 28.4. MS (*m/z*): 156 (*M*⁺, absent), 141 (100), 99 (52), 84 (8), 69 (38), 59 (18), 53 (21), 51 (8).

2.3. General procedure for carbonylation of acetylenic substrates and separation of products

A 300 ml stainless steel autoclave was charged with PdI₂ (36 mg, 0.1 mmol), KI (166 mg, 1.0 mmol) and a solution of acetylenic substrate (10 mmol) and water

(360 mg, 20 mmol) in anhydrous 1,4-dioxane (20 ml). The autoclave was purged several times with CO with stirring and eventually pressurized with CO (1.0 MPa) and if necessary with CO₂ (4.0 MPa at the saturation of the solution), then stirred and heated at 80 °C for 16 or 24 h. After cooling, the autoclave was degassed, the solvent evaporated and products separated by column chromatography (SiO₂).

2.4. Carbonylation of phenylacetylene in the presence of ¹³CO₂

An 8 ml stainless steel autoclave was charged with PdI₂ (2.1 mg, 0.0058 mmol), KI (9.7 mg, 0.058 mmol) and a solution of phenylacetylene (58 mg, 0.57 mmol) and water (20 μl, 1.1 mmol) in anhydrous 1,4-dioxane (1.2 ml). The autoclave was purged several times with CO with stirring and eventually pressurized with CO (1.0 MPa) and ¹³CO₂ (Isotec Inc., USA; ¹³C = 99%, ¹⁸O = 6%) (up to 4.0 MPa of stable pressure). The autoclave was heated at 80 °C for 24 h with stirring. GC–MS analysis proved that the reaction products did not contain ¹³C.

2.5. Pd–H formation from PdI₂, CO and H₂O in anhydrous dioxane

An 8 ml stainless steel autoclave was charged with PdI₂ (8.1 mg, 0.0225 mmol), KI (7.5 mg, 0.045 mmol), anhydrous dioxane-d₈ (1.5 ml) and water (40 μl, 2.25 mmol). The autoclave was purged several times with CO with stirring and eventually pressurized with CO (1.0 MPa), then heated at 80 °C for 16 h with stirring. After cooling, the autoclave was degassed, and 0.5 ml of the solution quickly transferred into a 5 mm NMR tube. The ¹H NMR spectrum showed a broad signal at –4.3 ppm.

2.6. Characterization of products

Identification of known products **1** and **1a** (R = *n*-Bu, Ph, *p*-MeC₆H₄) [14], **2** (R = Ph, *p*-MeC₆H₄) [15,16], **3** (R = *n*-Bu) [17] **5** [18,19], **6** [20] and **7** [21] was carried out by comparison with literature data. New compounds were identified by elemental analyses, IR, ¹H, ¹³C NMR, MS spectra and in some cases the assigned structures were confirmed by X-ray diffraction analyses.

Butylmaleic anhydride **2** (R = *n*-Bu), colorless oil. IR (neat) ν (cm⁻¹): 2960 (m), 2931 (m), 2869 (m), 1842 (m), 1772 (s), 1641 (m), 1463 (w), 1249 (m), 998 (w), 969 (w), 895 (m). ¹H NMR δ : 6.63–6.61 (m, 1H, =CH), 2.57–2.50 (m, 2H, CH₂CH₂CH₂CH₃), 1.64 (quint, *J* = 7.3 Hz, 2H, CH₂CH₂CH₂CH₃), 1.43 (sext, *J* = 7.3 Hz, 2H, CH₂CH₂CH₂CH₃), 0.96 (t, *J* = 7.3 Hz, 3H, CH₃). ¹³C NMR δ : 166.0, 164.2, 153.9, 128.6, 29.0, 25.7, 22.3, 13.6. MS (*m/z*): 154 (*M*⁺, <0.5%), 136 (1), 127 (17), 112 (100), 111 (23), 97 (8), 84 (38), 81 (28), 68 (12), 67 (17), 53 (13). Anal. Calcd for C₈H₁₀O₃: C, 62.31; H, 6.54. Found: C, 62.26; H, 6.52.

3,9-Diphenyl-1,6-dioxaspiro[4.4]nona-3,8-dien-2-one **4a** (R = Ph), colorless oil. IR (KBr) ν (cm⁻¹): 1763 (s), 1261 (m), 932 (w), 697 (w). ¹H NMR (DMSO-d₆) δ : 7.75–7.00 (m, 12H, 2Ph + 2CH), 3.64 (d, *J* = 7.3 Hz, 2H, CH₂). MS (*m/z*): 290 (*M*⁺, 63), 262 (51), 218 (57), 217 (72), 216 (42), 215 (100), 202 (57), 189 (13), 171 (15), 127 (24), 115 (52), 102 (43), 91 (42), 77 (22), 65 (13), 63 (16), 51 (19). Anal. Calcd for C₁₉H₁₄O₃: C, 78.60; H, 4.86. Found: C, 78.56; H, 4.84.

3,9-Di-*p*-tolyl-1,6-dioxaspiro[4.4]nona-3,8-dien-2-one **4a** (R = *p*-MeC₆H₄), colorless oil. IR (KBr) ν (cm⁻¹): 1762 (s), 1261 (m), 932 (w), 825 (m). MS (*m/z*): 318 (*M*⁺, 58), 290 (27), 246 (45), 245 (43), 231 (29), 230 (31), 229 (100), 216 (34), 215 (74), 202 (13), 185 (18), 141 (19), 129 (24), 128 (28), 115 (40), 105 (54), 91 (15), 77 (16), 65 (8), 63 (8), 51 (7). Anal. Calcd for C₂₁H₁₈O₃: C, 79.21; H, 5.70. Found: C, 79.16; H, 5.67.

3,8-Diisopropylidene-1,6-dioxaspiro[4.4]nonane-2,7-dione **8**, colorless crystals, mp 175 °C. IR (KBr) ν (cm⁻¹): 1764 (s), 1666 (m), 1279 (m), 1179 (m). ¹H NMR δ : 3.20 (d, *J* = 16.5 Hz, 2H, 2CH), 2.98 (t, *J* = 16.5 Hz, 2H, 2CH), 2.27 (s, 6H, 2CH₃), 1.90 (s, 6H, 2CH₃). ¹³C NMR δ : 167.0, 153.0, 117.5, 104.6, 38.9, 24.6, 20.1. MS (*m/z*): 236 (*M*⁺, 1), 218 (40), 190 (23), 175 (13), 162 (12), 149 (32), 96 (30), 67 (100), 53 (47), 41 (44). Anal. Calcd for C₁₃H₁₆O₄: C, 66.07; H, 6.83. Found: C, 66.04; H, 6.81. X-ray diffraction structural determination confirmed the assigned structure [22].

4,4'-Diisopropylidene-4H,4'H-[2,2']bifuranyl-5,5'-dione **9**, yellow crystals, mp 207 °C. IR (KBr) ν (cm⁻¹): 3102 (m), 1760 (s), 1631 (m), 1294 (w), 1009 (m), 901 (w). ¹H NMR δ : 6.48 (s, 2H, 2CH),

2.44 (s, 6H, 2CH₃), 1.25 (s, 6H, 2CH₃). ¹³C NMR δ : 161.2, 158.8, 157.1, 156.3, 142.2, 141.7, 122.4, 121.9, 109.0, 108.4, 24.8, 24.6, 21.3, 21.0. MS (m/z): 246 (M^+ , 75), 207 (13), 190 (22), 175 (23), 162 (22), 147 (18), 95 (51), 67 (100), 41 (49). Anal. Calcd for C₁₄H₁₄O₄: C, 68.27; H, 5.73. Found: C, 68.24; H, 5.72. X-ray diffraction structural determination confirmed the assigned structure [22].

4-Isopropylidene-2',2'-dimethyl-4H,2'H-[2,3']bifuranyl-5,5'-dione **10**, yellow crystals, mp 110 °C. IR (KBr) ν (cm⁻¹): 3110 (w), 2985 (m), 2932 (m), 1735 (s), 1640 (m), 1611 (m), 1254 (m), 1110 (m), 992 (m). ¹H NMR δ : 6.46 (s, 1H, =CH), 6.20 (s, 1H, =CH), 2.43 (s, 3H, CH₃), 2.19 (s, 3H, CH₃), 1.61 (s, 6H, 2CH₃). ¹³C NMR δ : 170.5, 165.1, 161.9, 158.7, 143.3, 122.5, 115.6, 110.1, 85.3, 26.4, 25.0, 21.5. MS (m/z): 234 (M^+ , 76), 219 (8), 191 (15), 148 (100), 91 (13), 67 (13), 53 (13). Anal. Calcd for C₁₃H₁₄O₄: C, 66.64; H, 6.03. Found: C, 66.61; H, 6.01.

3. Results

Products of reaction 1 were first examined. We caused an alkyne (10 mmol) to react with CO (1.0 MPa) and H₂O (360 μ l, 20 mmol) at 80 °C for

15 h in dioxane (20 ml) in the presence of the PdI₂ (0.1 mmol) and KI (1 mmol) catalytic system.

Beside compound **1**, its regioisomer **1a**, substituted maleic **2** and succinic anhydride **3** were formed (Fig. 1). In the case of arylacetylenes, products **4** formally deriving from 2 mol of alkyne, 3 mol of CO and 1 mol of H₂ were also formed. They turned out to be an isomeric mixture of mass 290 with phenylacetylene and 318 with tolylacetylene. Only one isomer could be separated sufficiently pure for analysis from isomers 290. Its formula can be written as shown in Fig. 1 on the basis the NMR spectrum. Different positions of the phenyl group and double bond shift may account for the other isomers.

We then studied the carbon dioxide effect on reaction 1 working under the same reaction conditions that led to furanones **1** but under carbon dioxide pressure (solvent saturation at 40 bar and room temperature). Anhydride **2** and lactone **1** were formed in comparable amounts [12].

Some comparative results obtained with and without additional carbon dioxide are reported in Table 1.

In spite of the remarkable change in selectivity from **1** to **2** due to the action of carbon dioxide, the carbon atom of the latter turns out not to be incorporated into the product. This point was proved by experiments

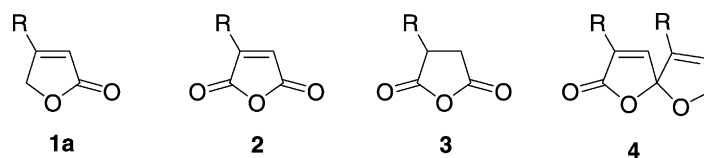


Fig. 1. By-products of reaction 1.

Table 1

Comparative reactions of 1-alkynes (10 mmol) with CO (1.0 MPa), CO₂ (4.0 MPa) and H₂O (20 mmol) in dioxane in the presence of PdI₂ (0.1 mmol) and KI (1 mmol), substrate concentration: 0.5 mmol/ml dioxane, $T = 80$ °C

R in RC≡CH	$P(\text{CO}_2)$ (bar)	t (h)	Conversion (%)	Yield (%) ^a				
				1	1a	2	3	4
<i>n</i> -Bu	–	15	98	77	8	7	3	–
<i>n</i> -Bu	40	64	93	32	10	47	6	–
Ph	–	15	100	67	Traces	1	Traces	22
Ph	40	24	91	30	2	34	2	12
<i>p</i> -MeC ₆ H ₄	–	24	98	75	1	1	–	11
<i>p</i> -MeC ₆ H ₄	40	24	97	31	1	38	–	10

^a Based on starting 1-alkyne, by GLC.

Table 2

Reaction of 3-methyl-1-butyne-3-ol (12 mmol) with CO (1.5 MPa) or CO (1.5 MPa) and CO₂ (3.5 MPa) and H₂O in dioxane (24 ml) in the presence of PdI₂ (0.1 mmol) and KI (1 mmol), 60 °C, 40 h

Run	P (bar)		H ₂ O		Conversion (%) ^a	Yield (%) ^a					
	CO	CO ₂	μl	mmol		5	6	7	8	9	10
1	15	–	480	26.67	96	72	6	1	12	–	2
2	15	35	480	26.67	93	80	1	–	6	–	2
3	15	–	240	13.33	87	68	1	1	14	–	1
4	15	35	240	13.33	88	76	–	–	7	–	1
5	15	–	120	6.67	77	60	–	–	6	10	–
6	15	35	120	6.67	81	67	–	–	3	4	3

^a Based on starting alkyne, by GLC.

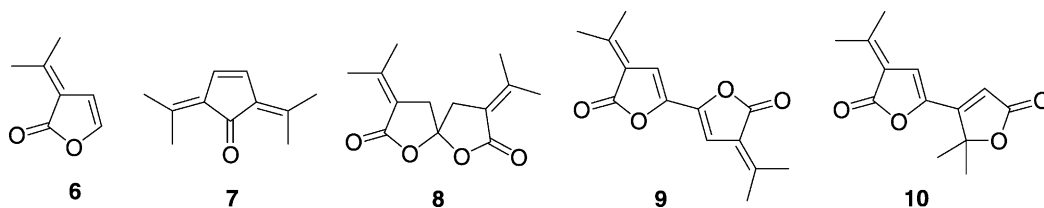
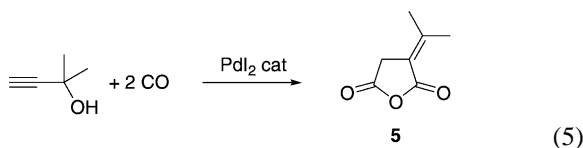


Fig. 2. By-products of reaction 5.

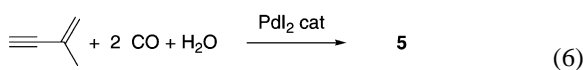
with ¹³CO₂, which showed that no significant ¹³C incorporation into the product occurred.

When we passed to other acetylenic compounds, containing an α-hydroxyl group, we observed a different behavior, which, however, could be rationalized according to known mechanism. We report here the outcome of the reactions performed with and without added carbon dioxide using 3-methyl-1-butyne-3-ol as starting material.

Under conditions similar to those adopted for reaction 1 (see Table 2), teraonic anhydride was formed in 72% yield through a formal additive carbonylation process (Eq. (5)).



Among by-products teraonic acid was formed in less than 2% yield. Similar results were obtained starting from 3-methyl-3-buten-1-yne (Eq. (6)).



Carbon dioxide curtailed the formation of most of by-products, shown in Fig. 2.

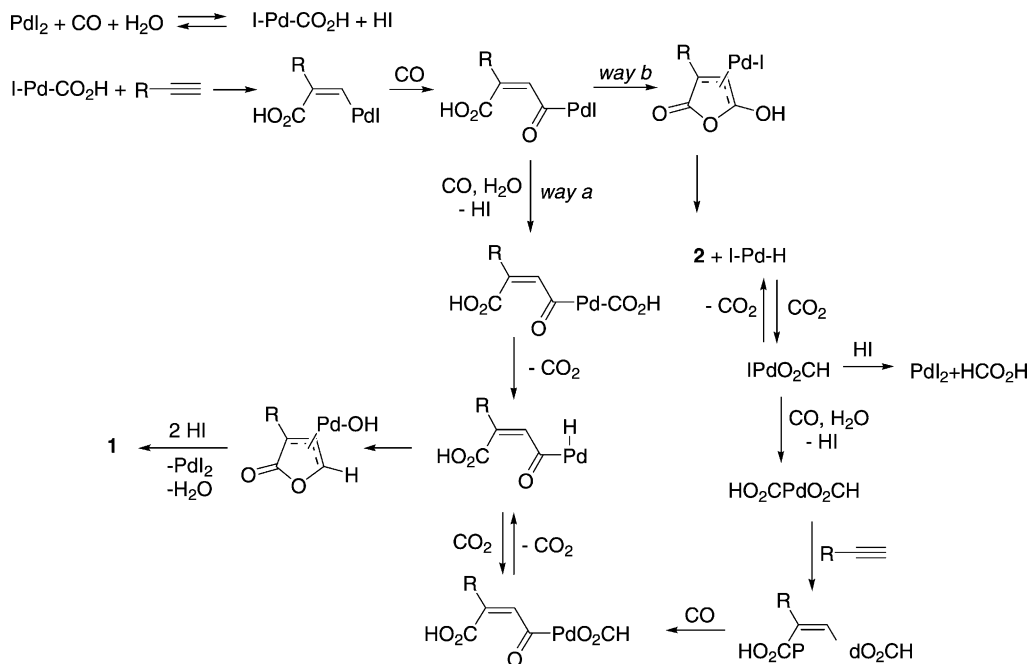
The structures of these compounds were determined by chemical, spectroscopic and X-ray diffraction (8 and 9) methods. Compounds 6–9 derive from reductive carbonylation, while 10 corresponds to additive carbonylation. The effect of carbon dioxide on their formation was a decrease of the percentage of only the reductive carbonylation products 6–9 in favor of compound 5. Water concentration also affected product distribution (Table 2).

We also observed that the percentage of by-products could be remarkably increased using a higher concentration of the alkyne in conjunction with a lower concentration of water. In particular compounds 7, 9 and 10 reached a percentage of more than 20% each when a mixture of 21 mmol of phenylacetylene, 25 μl of H₂O (1.39 mmol) and 0.5 ml of dioxane was used under the above conditions. No effort was made, however, to optimize yields.

4. Discussion

4.1. Formation of compound 1

Our interpretation of the reaction mechanism leading to lactone 1 is straightforward as far as the first



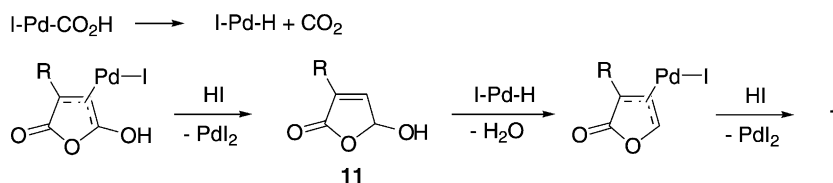
series of steps is concerned (Scheme 1, way a): it must involve the formation of a Pd–CO₂H species which inserts the alkyne and carbon monoxide in sequence, according to a well-established pattern. Reduction then takes place at the expenses of carbon monoxide, which is oxidized to carbon dioxide. This is likely to occur through further Pd–CO₂H formation from carbon monoxide and water and decomposition to palladium hydride and carbon dioxide according to way a, Scheme 1.

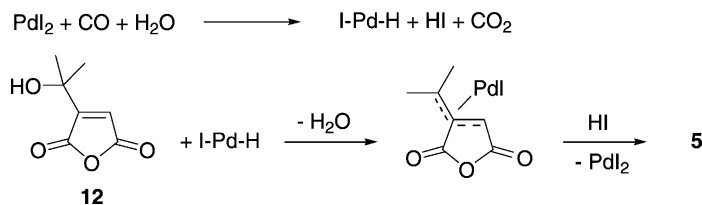
Palladium hydrides as reducing species are reported in [23]. Their intermediacy in reductive carbonylation of benzyl alcohols was proposed by Cavinato and Toniolo [24], and their reactions with allyl ether or esters was described [25]. Hydride-forming palladium catalysts have been reported to give formic acid or its

derivatives from carbon dioxide [26]. The presence of a Pd–H species under our conditions was supported by ¹H NMR in dioxane-d₈, which showed the presence of a broad signal at –4.3 ppm (see Section 2). A signal at –6.55 ppm was recently found for a palladium hydride, containing a water-soluble phosphine [27].

An alternative way might be followed if the hydroxylactone **11** were liberated and then reduced as an allyl compound (Scheme 2). Our system is in fact able to promote the reduction of allyl alcohols, as shown by the smooth transformation of 3-(1-hydroxy-1-methyl-ethyl)furan-2,5-dione **12** into anhydride **5** under the same reductive conditions used for the synthesis of lactones **1** (Scheme 3).

To clarify this point compound **11** (R = Ph) was prepared according to a procedure reported in [13] and





Scheme 3.

subjected to reaction with CO under the same conditions adopted for the reaction with phenylacetylene: only 6% of lactone **2** was found after the standard reaction time of 24 h, the starting hydroxylactone remaining mainly unconverted. To reach a 42% conversion 140 h were required. Even when the reaction was carried out in the presence of an alkyne, such as *p*-tolylacetylene, compound **11** remained mostly unconverted, while the alkyne gave the lactone corresponding to its own carbonylation. This behavior does not support the formation of lactone **11** shown in Scheme 2 as the intermediate of the main reaction path, although its reduction can occur slowly, probably via its palladium-coordinated precursors. Anhydride **2** also was shown not to be reduced to **1** under the same conditions.

4.2. Origin of compound 2

The catalytic formation of maleic anhydrides from alkynes and carbon monoxide has been reported so far to occur under oxidative conditions [28,29]. In our case, although no oxidant is added, the reaction affords a substantial amount of anhydride **2** catalytically in the presence of carbon dioxide under pressure.

In the absence of added carbon dioxide only a small amount (7% with *n*-butylacetylene, 1% with phenylacetylene) of anhydride **2** is formed under the conditions reported in Table 1. The remarkable increase of the anhydride yield achieved by adding carbon dioxide under pressure turned out not to be due to carbon dioxide incorporation into the anhydride molecule (which is formally possible by combining one molecule of the alkyne, one of carbon monoxide and one of carbon dioxide), as shown by the experiments with $^{13}\text{CO}_2$, where no ^{13}C incorporation was observed. The hydrogen originated by anhydride formation must instead be accepted by carbon dioxide with formation of a

palladium-formate bond through insertion into the Pd–H bond deriving from the ring tautomerization process that gives rise to anhydride **2**. The main reaction path in the presence of added CO₂ thus turns to be the one shown in Scheme 1, way b. The palladium-formate bond could in principle undergo protonolysis to regenerate PdI₂ with simultaneous formation of HCO₂H. However, formic acid was found to be present only to a small extent (less than 10% of that expected from a stoichiometric process) after acidification of the final reaction mixture. Therefore, the palladium formate species itself has to act as hydrogen-transfer agent from a palladium-bonded hydroxycarbonylpropynoyl chain to other acceptors, in particular to another hydroxycarbonylpropynoyl chain, forming one molecule of anhydride **2** and one molecule of lactone **1**. Scheme 1, way b, considers both the formation of formic acid and that of a palladium formate as a hydrogen-transfer agent, the latter being the main reaction path.

Formic acid and alkali formates were reported to act as reducing agents in conjunction with palladium catalysts [30–33]. Moreover acyl halides, formed in situ from aryl halides and carbon monoxide, were reduced to aldehydes with ammonium formate in the presence of a palladium catalyst [34]. The carbon dioxide effect must first imply a competition with carbon monoxide for coordination to palladium. Palladium complexes with carbon dioxide, stabilized by appropriate ligands, were reported in [35–37]. Once coordinated, carbon dioxide would accept hydrogen from the ring tautomerization process giving rise to anhydride **2** and an acylpalladium formate. Formate being a source of hydride, it can directly reduce the acylpalladium chain, giving rise to lactone **1** and carbon dioxide. Alternatively, protonolysis could give formic acid and restore the initial palladium(II) species. As mentioned above, only less than

10% of the formic acid expected to be formed by this process was found to be present in the reaction mixture. In a separate experiment we ascertained that free formic acid, if added to the reaction mixture in the absence of the alkyne under the mild conditions adopted for carbonylation, was not able to reduce the same 3-(1-hydroxy-1-methylethyl)-furan-2,5-dione that was mentioned above as being susceptible to reduction in the reductive carbonylation mixture. Accordingly, formic acid was found almost completely unaltered, while if present as palladium formate it was shown to be largely decomposed, thus confirming the role of the formate anion as hydrogen-transfer agent. That H-transfer may also occur via palladium formate is shown by reactions carried out in the presence of palladium formate (formed in situ from palladium iodide and potassium formate, with the latter and potassium iodide each in five-fold excess on palladium iodide): only lactone **1** was formed using phenylacetylene under standard conditions. In the presence of carbon dioxide (40 bar) the reaction rate strongly decreased, likely because carbon dioxide pressure retards formate decomposition, but still lactone **1** was predominant, anhydride **2** being less than 1%. This result should be compared with that obtained under carbon dioxide pressure but in the absence of added formate, which led to 1:1 ratio between lactone **1** and anhydride **2** in a combined yield of ca.70%. It can be concluded that although a formate excess has a negative influence on the rate the hydride is slowly delivered as well for reduction to **1**. This confirms the role of formate as hydrogen-transfer agent.

4.3. Origin of compound **4**

Let us now see the structure and way of formation of compound **4**. This compound forms according to a pathway similar to the one leading to **1** until the stage of its open-chained precursor (Scheme 4) where a new alkyne insertion is preferred to chain ring tautomerization. Further carbon monoxide insertion would lead to an analogous complex, which would be reduced in the same way. In agreement with Scheme 4, formation of **4** was favored at higher alkyne concentration as shown before.

Carbon dioxide influences the reaction course by blocking the insertion of a second molecule of alkyne,

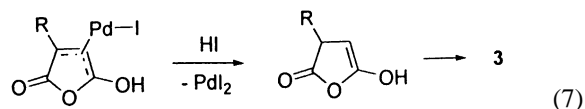
probably through competition for coordination to palladium, thus favoring the predominant formation of lactone **1** and anhydride **2**.

A recent paper [38] reporting the formation of anhydride **2** from alkyne carbon monoxide and water starting from PdCl₂ as catalyst deserves to be mentioned at this point. Although in our hands this procedure gave only a stoichiometric amount of **2** using an accurately deoxygenated solvent, it nevertheless shows that differently from our PdI₂-KI system where the Pd-CO₂H bond can act as a hydride transfer agent, the PdCl₂ system does not behave in this way, and anhydride formation occurs with concomitant reduction of Pd(II) to Pd(0).

4.4. Minor products

As to the formation of **1a**, it can be explained in the same way as that of **1** with the difference that the initial -CO₂H attack on the triple bond takes place at the less substituted end of the latter.

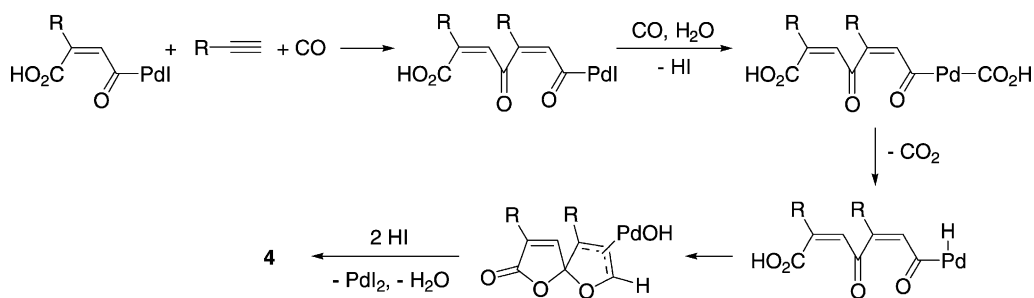
The presence of a small amount of the saturated anhydride **3** can be readily accounted for as deriving from protonation of the same intermediate involved in the synthesis of the maleic anhydride derivative **2** (Eq. (7)).



The formation of succinic anhydride has been reported recently [39].

4.5. Reaction of propynyl alcohol

Let us now see what happens when in the absence of added CO₂ a tertiary hydroxyl group is present on the carbon adjacent to the triple bond. In this case, the main reaction pathway corresponds to additive rather than reductive carbonylation, with formation of the tetraconic anhydride **5** previously described by Nogi and Tsuji [40]. Analogously to what we previously reported for the synthesis of aconitic acid from propynyl alcohol as well as for the synthesis of diethyl (*E*)-2-ethoxymethylsuccinate from diethyl acetal of prop-2-ynal [41,42], formation of tetraconic anhydride **5** could be interpreted as occurring



Scheme 4.

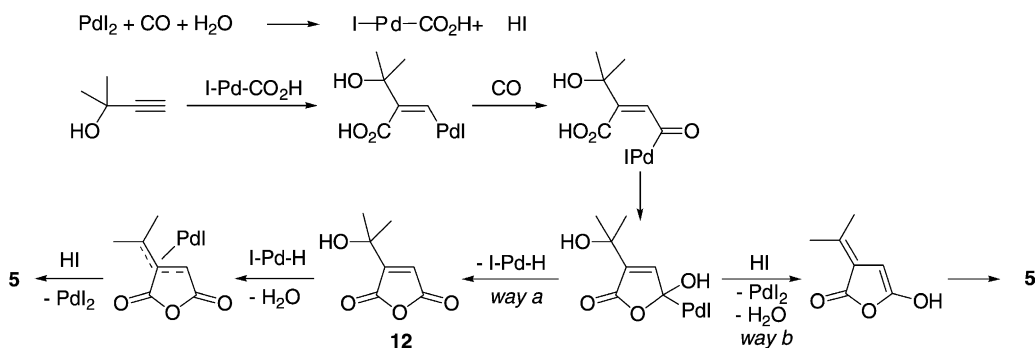
via oxidative dicarbonylation of the triple bond with formation of maleic anhydride **12** followed by reduction of the latter by H–Pd–I (Scheme 5, way a). That 3-(1-hydroxy-1-methylethyl)-furan-2,5-dione **12** could be reduced to **5** under the reaction conditions mentioned before (see above, Scheme 3), is a further evidence for the presence of a reducing species in the medium. However, if the formation of **5** from **12** occurred as depicted in Scheme 5, way a, working in the presence of added CO₂ (which, as we have seen before, is able to “trap” the Pd–H species with formation of palladium formate complexes) would cause **12** to accumulate in the reaction mixture at the expenses of **5**. Since this accumulation has not been observed we are left with an alternative pathway not involving liberation of H–Pd–I, as depicted in Scheme 5, way b.

In Scheme 5 the regiochemistry of I–Pd–CO₂H attack on the triple bond was shown as occurring in the same way as for simple alk-1-yne. The structures of by-products also reflect the same regiochemistry.

However, the regiochemistry of triple bond insertion of propynyl alcohol into the strictly analogous Pd–CO₂Me bond had been previously proven to be the opposite, owing to the steric effect exerted by the geminal methyl groups [43]. This means that, in contrast with –CO₂Me, the steric hindrance of the –CO₂H group is not sufficient to cause regioselectivity inversion with respect to that usually observed with alkynes not containing bulky substituents.

The origin of by-products **6–10** could be reasonably explained through known reaction pattern. We refrain, however, from proposing mechanistic details, which require further investigation. It is however interesting to note that the decreasing of selectivity in reductive carbonylation products (**6–9**) observed in the presence of an excess of CO₂ is in agreement with our interpretation, i.e. that the carbon dioxide effect is mainly due to hydride uptake as a palladium-bonded formate.

In conclusion the carbon dioxide effect observed in the present study has to be attributed to hydride trapping by CO₂, which leads to a palladium-bonded



Scheme 5.

formate able to start a new oxidative carbonylation cycle through Pd–CO₂H bond formation. In agreement with this interpretation CO₂ addition exerts a positive effect on oxidative carbonylation processes every time reduction products, formed through the action of a palladium hydride species, are present in oxidative carbonylation carried out in the absence of oxygen.

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