Reactivity of mono- and di-methoxycarbonyl complexes of Pd^{II} towards amines and copper amine complexes: role of copper in the catalyzed palladium–copper oxidative carbonylation of amines *

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Abstract

The reactivity of mono- and di-methoxycarbonyl complexes of palladium of formula $[PdL_2Cl_{2-n}(COOCH_3)_n]$ ($n = 1$ or 2; L_2 = chelating ligand) towards amines in the presence of $[RNH_3]Cl$ or $CuCl_2$ has been studied. The reactions yield *N,N′*-disubstituted ureas or carbamates, respectively. These results are compared with the dioxygen-induced carbonylative oxidation of amines catalyzed by palladium-based systems.

Key words: Palladium; Copper; Carbonylation; Amine; Urea; Carbamate

1. Introduction

Palladium salts or complexes in the presence of acids and/or copper salts as co-catalysts have been used [1–4] in the oxidative carbonylation of amines for the synthesis of *N,N′*-disubstituted ureas and carbamates (eqns. (1) and (2)).

$$2RNH_2 + CO + 1/2O_2 \longrightarrow CO(NHR)_2 + H_2O \quad (1)$$

$$RNH_2 + CO + R'OH + 1/2O_2 \longrightarrow CO(NHR)(OR') + H_2O \quad (2)$$

A mechanism involving a redox process is generally considered to be involved (Scheme 1).

Ureas or carbamates are formed in the reductive step (i) (eqn. (3) or (4)), while the catalytically active Pd^{II} species is restored in the oxidative process, steps (ii) or (iii).

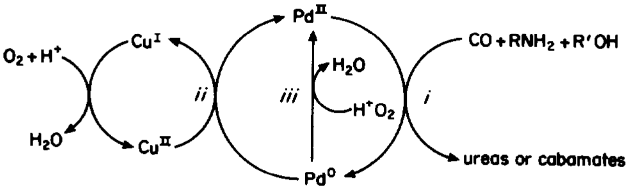
$$Pd^{II} + CO + 2RNH_2 \longrightarrow Pd^0 + CO(NHR)_2 + 2H^+ \quad (3)$$

$$Pd^{II} + CO + RNH_2 + R'OH \longrightarrow Pd^0 + CO(NHR)(OR') + 2H^+ \quad (4)$$

Acids or copper salts as co-catalysts have been used to speed the oxidative step. In the presence of acids alone, the Pd^0 oxidation (step iii) proceeds according to the stoichiometry of eqn. (5), whereas in the other case, Cu^{II} oxidizes the Pd^0 as in the Wacker process with the dioxygen acting as reoxidant of Cu^I (step ii).

$$Pd^0 + 2H^+ + 1/2\,O_2 \longrightarrow Pd^{II} + H_2O \quad (5)$$

Although the above catalytic systems are closely related and alkoxycarbonyl or carbamoyl complexes were presumed to be key intermediates for eqns. (3) and (4), respectively, the selectivity towards reaction products and working conditions is very different [1–4]. The different reactivity of supposed alkoxycarbonyl or car-



Scheme 1.

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* Dedicated to Professor A. Sacco on the occasion of his 70th birthday and in recognition of his important teaching.

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$$[PdL_2Cl_{2-n}(COOCH_3)_n] + RNH_2 + [RNH_3]Cl \longrightarrow N,N'\text{-urea}$$

Scheme 2.

bamoyl intermediates cannot account alone for this behaviour. We infer that different reactions can be promoted, depending on the presence of acids or/and copper salts.

In order to verify this hypothesis, the reactivity of Pd^{II} carbomethoxy complexes towards amines, in the presence of $[RNH_3]Cl$ or $CuCl_2$, has been studied.

2. Results and discussion

Mono- and di-methoxycarbonyl complexes of palladium of formula $[PdL_2Cl_{2-n}(COOCH_3)_n]$ [$n = 1$ or 2; L_2 = bipyridine (bipy) or 1,10-phenanthroline (phen)] have been prepared by carboxymethylation of the corresponding Pd^{II} complexes (eqn. (6)) [5].

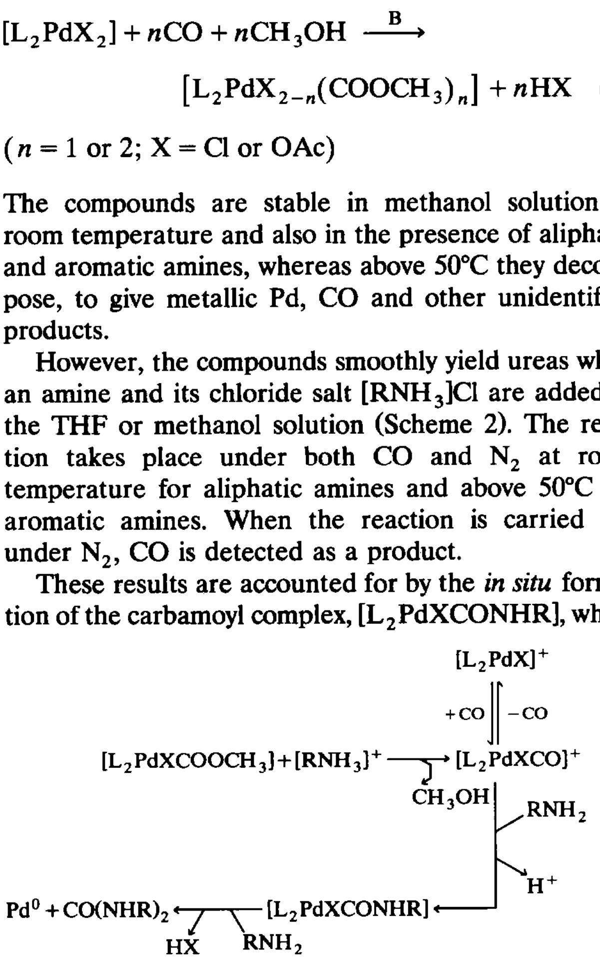
$$[L_2PdX_2] + nCO + nCH_3OH \xrightarrow{B} [L_2PdX_{2-n}(COOCH_3)_n] + nHX \quad (6)$$

($n = 1$ or 2; X = Cl or OAc)

The compounds are stable in methanol solution at room temperature and also in the presence of aliphatic and aromatic amines, whereas above 50°C they decompose, to give metallic Pd, CO and other unidentified products.

However, the compounds smoothly yield ureas when an amine and its chloride salt $[RNH_3]Cl$ are added to the THF or methanol solution (Scheme 2). The reaction takes place under both CO and N_2 at room temperature for aliphatic amines and above 50°C for aromatic amines. When the reaction is carried out under N_2, CO is detected as a product.

These results are accounted for by the *in situ* formation of the carbamoyl complex, $[L_2PdXCONHR]$, which then produces urea by reaction with amine. It is very likely that the carbamoyl complex forms by acid decomposition of the methoxycarbonyl complex, as depicted in Scheme 3. The carbon monoxide in the gas phase would originate from the supposed Pd^{II} carbonyl intermediate $[L_2PdXCO]^+$.



Scheme 3.

These results show that Pd–methoxycarbonyl complexes are not able to produce carbamates by reaction with amines under mild reaction conditions. Therefore, their formation under the conditions described in [3] should be due to a mechanism different from that proposed. On the contrary, these results are in agreement with our previous observations [1,2], showing that urea is selectively produced when a palladium(II) complex is allowed to react with an amine and its ammonium salt in methanol solution under CO at room temperature. However, when anhydrous $CuCl_2$ instead of $[RNH_3]Cl$ is added to a methanol suspension of mono- or di-methoxycarbonyl complex containing an aliphatic or aromatic amine, carbamate and not urea is obtained. Similar results are obtained when $[CuCl_2(RNH_2)_2]$ ($R = {}^nBu$ or Ph) is allowed to react in methanol with Pd complexes in the absence of free amine.

In order to gain some insight into the reaction stoichiometry, we carried out the reaction both under N_2 and CO, using different Cu/Pd molar ratios. Under N_2 in the presence of the mono(methoxycarbonyl) complex, the maximum yield of carbamate is obtained for a Cu/Pd ratio of 2:1, whereas a ratio of 4:1 is needed when di(methoxycarbonyl) complex is used.

However, when the reactions are carried out under CO, the carbamate yields increase with the amount of copper. This suggests that $CuCl_2$ or its amine complex can also promote directly the carbonylation of amine to carbamate.

We have been able to show that carbamates obtained in the reaction with Pd complexes form through two different routes. The first is a direct carboxymethylation of amines promoted by only Cu^{II}. This reaction takes place when $CuCl_2$ is added under CO to a methanol solution of an amine or when the amine complex $[CuCl_2(RNH_2)_2]$ ($R = {}^nBu$ or Ph), is allowed to react with CO and methanol (eqn. (7)). The second involves an interaction between the Pd methoxycarbonyl complex and the amine copper complex (eqns. (8) and (9)).

While some support can be found in the literature for eqn. (7) [6], eqns. (8) and (9) are unexpected and quite unprecedented.

$$2[CuCl_2(RNH_2)_2] + CH_3OH + CO \longrightarrow CO(NHR)(OCH_3) + 2CuCl + 2[RNH_3]Cl + RNH_2 \quad (7)$$

($R = {}^nBu$ or Ph)

$$[L_2PdClCOOCH_3] + 2[CuCl_2(RNH_2)_2] \longrightarrow [L_2PdCl_2] + 2CuCl + RNHCOOCH_3 + [RNH_3]Cl + 2RNH_2 \qquad (8)$$

$$[L_2Pd(COOCH_3)_2] + 4[CuCl_2(RNH_2)_2] \longrightarrow [L_2PdCl_2] + 4CuCl + 2RNHCOOCH_3 + 2[RNH_3]Cl + 4RNH_2 \qquad (9)$$

(L_2 = bipy or phen)

The stoichiometry of eqns. (7)–(9) has been determined by GLC of the organic product and isolation of the complex (see Experimental section). The presence of carbamate has also been confirmed by IR and MS spectra of reaction solutions. The IR spectra show a band between 1730 and 1700 cm^{-1}, typical of a carbamate [7]. An additional band at 2080 cm^{-1}, probably due to a Cu^I carbonyl complex [8], is also present in the case of eqn. (7).

Additional comments are required for eqns. (8) and (9), as they afford a new phosgene-free synthesis of carbamates. Support for direct interaction of two complexes is provided by the following considerations. Possible alternative carbamate formation by reaction between the methoxycarbonyl complex of palladium and the free amine from dissociation of the copper amine complex is ruled out. As we report above, the Pd complexes are stable under mild conditions, while under more drastic conditions, they afford urea and not carbamate.

Decarbonylative decomposition of Pd methoxycarbonyl complexes and subsequent methoxycarbonylation of $[CuCl_2(RNH_2)_2]$ ($R = {}^nBu$ or Ph) giving carbamates, according to eqn. (7), has also to be excluded. Whereas methoxycarbonyl complexes react at room temperature under N_2 with $[CuCl_2(RNH_2)_2]$ ($R = {}^nBu$ or Ph) giving carbamate, $[CuCl_2(PhNH_2)_2]$ reacts with CO and methanol only at temperatures above 50°C.

As far as the reaction mechanism is concerned, it is very likely that the interaction gives chloroformate which then produces carbamate by reaction with amine. Support for this is the experimental evidence [5b] that $[PdL_2(COOCH_3)_2]$ (L_2 = bipy or phen) reacts with anhydrous $CuCl_2$ in THF to give chloroformate (eqn. (10)).

$$\underset{(2)}{[L_2Pd(COOCH_3)_2]} + 4CuCl_2 \xrightarrow{THF} [PdL_2Cl_2] + 4CuCl + 2ClCOOCH_3 \qquad (10)$$

3. Conclusions

This study illustrates reaction conditions necessary for converting Pd–methoxycarbonyl complexes into urea or carbamate stoichiometrically. The conversion can also be carried out catalytically using a mixture of CO/O_2 [9].

These results can shed light on the role of Cu^{II} in the Pd-catalyzed synthesis of ureas and/or carbamates by dioxygen-induced carbonylative oxidation of amines [1–4]. Carbamates can be obtained under mild conditions when only $CuCl_2$ is added as co-catalyst to palladium. In this case, copper has three functions. It can reoxidize Pd^0, as in the Wacker process (Scheme 1, step ii), promote the cleavage of the Pd–C bond in the Pd–$COOCH_3$ moiety to give chloroformate which then reacts with amine to afford carbamate (eqn. (10)), and catalyze alone the direct carbonylation of amines to carbamates (eqn. (7)).

4. Experimental details

All operations were carried out using standard Schlenk techniques under oxygen-free N_2. Solvents were dried by standard methods, and stored under N_2. Amines were distilled from CaO before use. Complexes $[Pd(OAc)_2L_2]$ were prepared in methanol by reaction of $Pd(OAc)_2$ with the appropriate L_2 in a 1:1 ratio [10]. Mono- and di-methoxycarbonyl complexes $[PdL_2Cl_{2-n}(COOCH_3)_n]$ were prepared as described in [5b]. The Fluka Chemie commercial products $CuCl_2$ and $CuCl_2 \cdot 2H_2O$ were used as purchased. IR spectra were recorded on a Perkin Elmer 883 spectrophotometer. GC-MS analyses were performed using a Hewlett Packard 5995 instrument. The GLC quantitative analyses of carbamates were carried out with a Varian Vista 6000 connected to a Varian 4270 integrator using a SP-2100/0.1% carbowax column and toluene as internal standard.

4.1. General procedure for the reactions of methoxycarbonyl complexes

4.1.1. With amines and amine hydrochlorides: N,N′-disubstituted urea syntheses

A mixture of $[Pd(COOCH_3)_2bipy]$ (0.324 g, 0.90 mmol), $[BuNH_3^+]Cl$ (1.04 g, 2.04 mmol) and an excess of $BuNH_2$ (0.5 ml) in THF (10 ml) was stirred under CO at room temperature until decomposition of the green complex suspension to black metallic palladium (about 0.5 h) occurred. The IR spectrum of the filtered reaction solution showed a band at 1665 cm^{-1} attributed to ν(CO) of *N*,*N*′-dibutylurea. The presence of urea was also confirmed by mass spectrometry. MS: 172 (M^+, relative intensity 37%), 101 (20%), 100 (15%), 74 (32%), 57 (33%), 44 (100%). Removal of the solvent *in vacuo* and cooling to −5°C of the hexane fraction extracted from the crude semi-solid residue gave *N*,*N*′-dibutylurea as colourless crystals. A similar result was obtained when the reaction was carried out under dinitrogen.

The reactions with other complexes were carried out according to the above procedure. Mono-methoxycarbonyl complexes were used with a Pd/$[BuNH_3]^+$ molar ratio of 1 : 1. *N,N'*-Diphenylurea was obtained when aniline was used as amine. The urea was identified by IR and mass spectra. The IR spectrum in Nujol was identical with that of a pure sample of $CO(NHPh)_2$.

4.1.2. With $[CuCl_2(^nBuNH_2)_2]$: carbamate synthesis and stoichiometry of reaction

$[Pd(COOCH_3)_2bipy]$ (0.240 g, 0.63 mmol), in THF (5 ml) and $CuCl_2$ (0.706 g, 2.52 mmol) were loaded separately in the two branches of an inverted-Y glass reactor. The reactor was closed under dinitrogen and the contents were mixed. After 1 h of stirring, the liquid phase of the reaction mixture was analysed. The IR spectrum showed a band at 1726 cm^{-1}, due to the CO stretch of $BuNHCOOCH_3$, which was also confirmed by GC-MS spectrum and GLC analysis. MS: m/z 131 (M^+, 9%), 88 (100%), 59 (17%), 57 (12%), 44 (52%). GC quantitative analysis gave 0.130 g of $BuNHCOOCH_3$ (yield 79% based on the initial palladium complex and stoichiometry of eqn. (9)).

The solid reaction residue was filtered off in strictly anaerobic conditions, due to the great sensitivity of Cu^I to oxygen, and the components ($[PdCl_2bipy]$ and CuCl) were separated by the addition of a methanol solution (10 ml) containing bipyridine (2.5 mmol). The pale-yellow residue was filtered off and identified as $[PdCl_2(bipy)]$ by elemental analyses and its IR spectrum. Anal. Found: C, 35.8; H, 2.2; Cl, 21.2; N, 8.3; Pd, 31.7. $C_{10}H_8Cl_2N_2Pd$ calcd.: C, 35.99; H, 2.42; Cl, 21.26; N, 8.40; Pd, 31.91%.

The red-brown solution collected after the removal of methanol *in vacuo* gave a brown solid whose elemental analyses were consistent with the bipyridine complex [CuCl(bipy)]. Anal. Found: C, 46.8; H, 3.0; Cl, 14.1; Cu, 24.8; N, 10.7. $C_{10}H_8ClCuN_2$ calcd.: C, 47.07; H, 3.16; Cl, 13.89; Cu, 24.90; N, 10.97%.

The Cu/Pd stoichiometric molar ratio was deduced by carrying out the reaction with an excess of Cu^{II} and titrating the Cu^{II} residue by iodometry according to the following procedure: $[Pd(COOCH_3)_2bipy]$ (0.160 g, 0.42 mmol) and an excess of $[CuCl_2(BuNH_2)_2]$ (0.589 g, 2.10 mmol), Cu/Pd = 5, were allowed to react as described above. Acetic acid and potassium iodide were added under dinitrogen to a de-aerated aqueous suspension of solid reaction residue, and the liberated iodine was titrated with a standard 0.1 N $Na_2S_2O_3$ solution; 4.3 ml of solution, corresponding to 0.43 mmol of Cu^{II} unreacted were needed to reach the starch end point. Reactions with other complexes or with amines and $CuCl_2$ were carried out according to the procedure described above.

When aniline or $[CuCl_2(PhNH_2)_2]$ was used, $PhNHCOOCH_3$ was obtained. Carbamate was identified by IR (THF): ν(CO) 1726 cm^{-1}. MS: m/z 151 (M^+, 68%), 120 (13%), 119 (65%), 106 (100%), 92 (46%), 77 (39%), 65 (89%), 59 (37%), 39 (74%).

4.2. Methoxycarbonylation of copper complexes

$[CuCl_2(BuNH_2)_2]$ (0.510 g, 1.82 mmol) in methanol saturated with carbon monoxide (10 ml), was allowed to react with 1 atm of CO at 70°C as the green colour lightened (about 4 h). The reactor was cooled to room temperature (22°C) and the volume of unreacted carbon monoxide was measured with a gas burette (22.6 ml; Cu/CO $\approx$ 2). The IR spectrum of solution showed bands at 1703ms cm^{-1} due to $BuNHCOOCH_3$, and at 2080w cm^{-1}. The GLC quantitative analysis gave 0.101 g of $BuNHCOOCH_3$ (85% yield based on copper and stoichiometry of eqn. (7)). The mass spectrum of carbamate was identical with that reported above. The Cu^I present in the solution was determined as a solid complex obtained by adding a suitable ligand. Addition of PPh_3 (0.480 g) gave the triphenylphosphine complex $[CuCl(PPh_3)]$. Anal. Found: Cu, 10.2; Cl, 5.7; P, 9.8. $C_{36}H_{30}ClCuP_2$ calcd.: Cu, 10.20; Cl, 5.69; P, 9.95%.

References

1 P. Giannoccaro, *J. Organomet. Chem.*, *336* (1987) 271.

2 P. Giannoccaro, *Inorg. Chim. Acta*, *142* (1988) 81

3 H. Alper and F.W. Harstock, *J. Chem. Soc., Chem. Commun.*, (1985) 1141; H. Alper, G. Vasapollo, F.W. Hartstok and M. Mlekuz, *Organometallics*, *6* (1987) 2391.

4 S. Fukuoka, M. Chono and M. Kohno, *J. Organomet. Chem.*, *83* (1884) 99.

5 (a) P. Giannoccaro, *VII - I.S.H.C.*, Lyon, France, 1990, P120, p. 377; (b) P. Giannoccaro, N. Ravasio and M. Aresta, *J. Organomet. Chem.*, *451* (1993) 243.

6 W. Brackman, *Chem. Abstr.*, *55* (1961) 22345e and 22343i.

7 C.J. Pouchert, *The Aldrich Library of Infrared Spectra*, Aldrich Chemical Company, 1970.

8 M. Pasquali, C. Floriani, G. Venturi, A. Gaetani-Manfredotti and A. Chiesi-Villa, *J. Am. Chem. Soc.*, *104* (1982) 4092.

9 P. Giannoccaro, unpublished results.

10 C. D'Agostino, Thesis, University of Bari, 1992.