Carbonylation of Dinitrotoluene to Dimethyl Toluenedicarbamate; High Efficiency of Phosphorus Acids as Promoters for the Palladium-Phenanthroline Catalytic System

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Abstract: Phosphorus acids are excellent promoters for the palladium-phenanthroline catalyzed carbonylation of 2,4-dinitrotoluene to 2,4-toluenedicarbamate. For the first time, all intermediate nitrocarbamates and aminocarbamates have been independently synthesized and their amount after every catalytic reaction precisely quantified. An extensive optimization of all experimental variables has been carried out. The best acids are phenylphosphonic and 4-tolylphosphonic acids. The addition of 2,2-dimethoxypropane as an internal drying agent is highly beneficial. The addition of an amine derived from the starting dinitroarene increases both rate and selectivity of the carbonylation reaction. The complexes $[Pd(Phen)_2][SbF_6]$ and $[Pd(Phen)_2][BAr^F_4]$ $[Ar^F = 3,5\text{-}(CF_3)_2C_6H_3]$ have been prepared for the first time. The latter displays a markedly higher solubility than all other $[Pd(Phen)_2]^{2+}$ complexes. The effect of several possible promoters has also been investigated. Under the optimized experimental conditions, a 77.6% selectivity in dicarbamate was obtained when working at a molar ratio dinitrotoluene/Pd = 2920. At the end of the reaction, the dicarbamate spontaneously precipitates out of the solution in high yields upon cooling, with no inclusion of the acid promoter or of phenanthroline. 2,6-Dinitrotoluene can also be efficiently carbonylated to the corresponding dicarbamate.

Keywords: carbamates; carbonylation; homogeneous catalysis; nitroarenes; palladium

Introduction

2,4-Toluenediisocyanate (TDI) is a key component for the production of polyurethanes and is actually produced worldwide on a more than 5 millions tons per year scale by a process employing the highly toxic phosgene. Carbonylation of nitroarenes in the presence of alcohols to afford carbamates [Eq. (1)], followed by thermal cracking to give the corresponding isocyanate [Eq. (2)] has been considered as a safer alternative towards these products.[1–3] However, no commercial process has been developed up to now that can compete with the actual technology, mainly because of the insufficient turnover numbers achievable even with the best catalytic systems and the associated cost of recycling the metal and the ligand.

$$ArNO_2 + ROH + 3\,CO \xrightarrow{cat.} ArNHCOOR + 2\,CO_2 \qquad (1)$$

$$ArNHCOOR \xrightarrow{\Delta} ArNCO + ROH \qquad (2)$$

Moreover, carbonylation of dinitrotoluene is a difficult task and many catalytic systems that show a good activity in the carbonylation of nitrobenzene fail completely to carbonylate dinitrotoluene or afford at best very poor yields.[1–3] One reason for this is that many catalytic cycles proceed through an intermediate reduction of the nitroarene to the corresponding aniline, which is only later carbonylated. In the case of dinitroarenes, the nitro and amino groups that are formed in this first step deactivate each other; the nitro group decreasing the nucleophilic power of the amino one and the latter decreasing the oxidizing power of the first. In recent years the catalytic system based on palladium-phenanthroline complexes has emerged as the most active and promising for a possible industrial application.[4–35] This is also one of the few catalytic systems that have been reported to be successful even for dinitroarenes, although selectivities are only moderate. Very recently, we reported that phosphorus acids such as phenylphosphonic and especially phosphoric acid are excellent promoters for the palladium-phenanthroline catalytic system and allowed us to reach an unprecedented turnover frequency of

6000/h and a total turnover number of 10^5 in the case of nitrobenzene.[34,35] We have now extended the use of the new promoters to the carbonylation of dinitrotoluene and performed an optimization study of the experimental conditions.

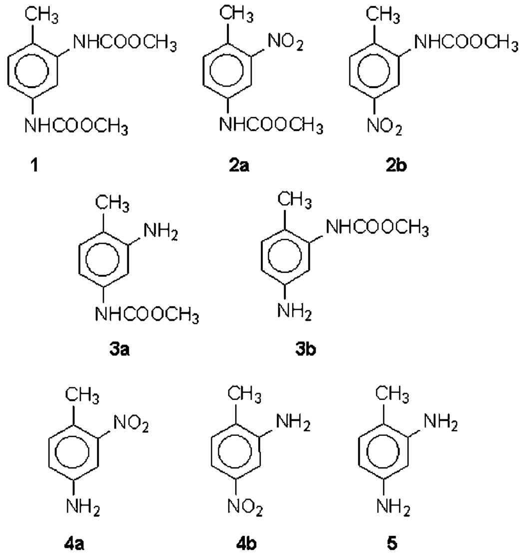
Results and Discussion

Independent Synthesis of the Organic Intermediates or Byproducts

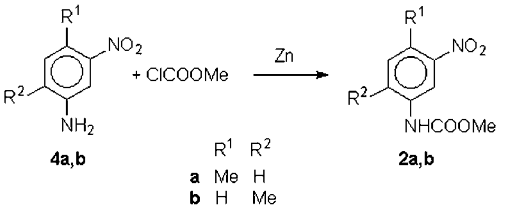
The first problem which is encountered when dealing with the carbonylation of 2,4-dinitrotoluene is the large number of possible intermediates and byproducts. Apart from the desired dicarbamate (**1**), there are two nitrocarbamates (**2a, b**), two aminocarbamates (**3a, b**), two nitrotoluidines (**4a, b**), diaminotoluene (**5**) (Scheme 1) and a virtually unlimited number of azo- and azoxyarenes, and ureas. In this work we have independently synthesized all the nitro- and aminocarbamates and quantified all the products reported in Scheme 1 for all reactions.

Despite the fact that the **2** and **3** are often mentioned as byproducts in carbonylation reactions of 2,4-dinitrotoluene, an independent synthesis and a full characterization of these compounds has not been previously reported in the literature.

The two nitrocarbamates **2** were obtained by reaction of the corresponding nitroanilines **4** with methyl chloroformate in the presence of metallic zinc [Eq. (3)], following a protocol already shown in the literature to give good results for the synthesis of carbamates in which the aryl group bears electron-withdrawing substituents.[36]

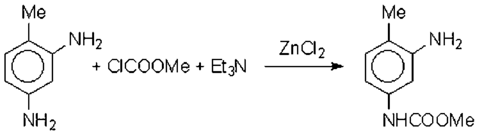


Scheme 1. Numbering scheme for the products derived from 2,4-dinitrotoluene.



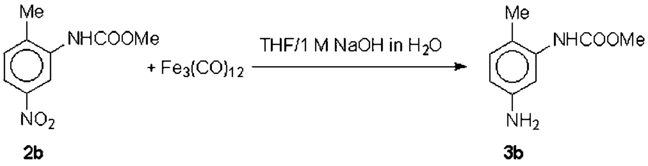
(3)

Reaction of **5** with methyl chloroformate in the presence of $ZnCl_2$ and triethylamine gave **3a** almost exclusively [Eq. (4)] and the pure product could be isolated by crystallization free of any **3b**.



(4)

Compound **3b** was obtained by reduction of the corresponding nitrocarbamate by $Fe_3(CO)_{12}$, following our modification[37] of the procedure originally reported by Alper and coworkers.[38] This procedure is very selective and quite convenient on the laboratory scale [Eq. (5)]. The carbamate group was not reduced or hydrolyzed to any detectable extent under these conditions.



(5)

By analogy with the related carbonylation of nitrobenzene, it is expected that the main byproducts will be azoxy compounds. However, as previously mentioned, many different such compounds may be formed and we did not consider it worth targeting the synthesis of any of them, even because no other clearly defined peak could be observed in the HPLC analyses of most of the catalytic reactions, apart for those attributable to the compounds in Scheme 1. Only when a reaction was performed in the absence of promoters, a red compound could be isolated from the reaction mixture, which was identified by its mass spectrum as $(O_2N)(CH_3)C_6H_3\text{-}N{=}N(O)C_6H_3(CH_3)(NO_2)$, but the exact substitution pattern (nitro groups in the 2- or 4-position) could not be assessed.

Synthesis of the Catalysts

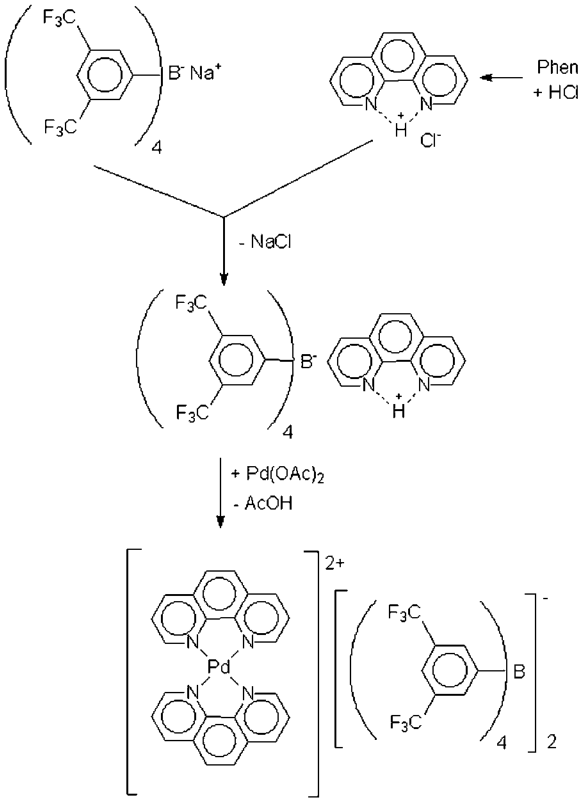
Throughout most of this study we employed $[Pd(Phen)_2][BF_4]_2$ as the catalyst. The non-coordinating nature of the BF_4^- is essential in order for high catalytic activity to be observed. The use of the corresponding hexafluorophosphate salt has also been reported in the literature, but, in our previous work on the carbonylation of nitrobenzene, we showed this compound to give slightly worse results in combination with phosphorus acids. In our quest for more reactive catalysts for the carbonylation reactions of nitroarenes, we decided to target the synthesis of the $[Pd(Phen)_2]^{2+}$ salts with the SbF_6^- and $BAr^F{}_4^-$ [$Ar^F = 3,5\text{-}(CF_3)_2C_6H_3$] anions. Hexafluoroantimonate is known to be chemically very stable, whereas $BAr^F{}_4^-$ is one of the least interacting anions known to date. It generally imparts to its compounds solubilities in low or medium polarity solvents not achievable with any other anion and the corresponding $[Pd(Phen)_2]^{2+}$ salt may become useful as catalyst even for other reactions when this feature is relevant. It should also not be forgotten that the $BAr^F{}_4^-$ shows a much lower tendency to transfer one of its aryl groups as compared to the analogous BPh_4^- anion.[39,40]

Basically, three different syntheses have been reported for complexes of the type $[Pd(Phen)_2][X]_2$ for which the corresponding palladium salt is not available:

1) Anion exchange between $[Pd(Phen)_2][NO_3]_2$ and NaX, the first being directly obtained from palladium nitrate and Phen.[7]
2) Reaction of $PdCl_2(CH_3CN)_2$ with AgX in CH_3CN, to intermediately afford $[Pd(CH_3CN)_4][X]_2$, followed by reaction with Phen.[14]
3) Reaction of $Pd(OAc)_2$ with the phenanthrolinium salt [PhenH][X], obtained by reaction of Phen with the corresponding acid.[41] The [PhenH][X] salt can also be prepared in some cases by reaction of Phen with HCl in the presence of a salt of X^- (e.g., NH_4X), provided the desired compound is less soluble than [PhenH][Cl].[41]

The first method requires the desired $[Pd(Phen)_2][X]_2$ to be less soluble (in acetone) than the starting nitrate analogue. The second requires the availability of the silver salt of the final anion and the third necessitates of the corresponding acid or the solubility order mentioned should be fulfilled.

The conditions for the first method are met by the SbF_6^- anion and the corresponding palladium-phenanthroline complex was synthesized without difficulties by this strategy (see Experimental Section for details). However, the conditions for neither of the first two methods are met by $BAr^F{}_4^-$. Moreover, the acid $HBAr^F{}_4$ has been reported in the literature (as the etherate),[42] but its synthesis is very delicate and the compound is stable only at low temperatures. Despite some attempts, we could not obtain analytically pure samples of [PhenH][$BAr^F{}_4$] by reaction of the so obtained acid with phenanthroline, because the high solubility of this salt compared to the ones with other anions prevented its purification from excess amounts of any of the two starting reagents by crystallization.



Scheme 2. Synthesis of $[Pd(Phen)_2][BAr^F{}_4]_2$.

We thus decided to follow a double exchange strategy (Scheme 2). First $NaBAr^F{}_4$[42,43] and [PhenH][Cl] were independently synthesized. The two compounds were dissolved in methanol and the resulting solution was dried under vacuum. Treatment of the residue with diethyl ether left NaCl as a solid residue, which was filtered off. Evaporation of the ether solution afforded the crude yellowish product, which was purified by Soxhlet extraction of the impurities with hexane to afford the colorless analytically pure [PhenH][$BAr^F{}_4$].

Treating $Pd(OAc)_2$ with two equivalents of [PhenH][$BAr^F{}_4$] in acetone gave the desired product and AcOH. It should be noted that the original recipe for this last step employs a 50% molar excess of [PhenH][X] with respect to stoichiometry, and the insoluble product is isolated by filtration. However, $[Pd(Phen)_2][BAr^F{}_4]_2$ is completely soluble in acetone under the conditions employed. Thus it is essential to use the exact reagent amounts in order to obtain a pure product. The product is isolated by drying the reaction solution under vacuum and washing the residue with hexane, to afford the analytically pure product as a pale brown powder.

The solubility of $[Pd(Phen)_2][BAr^F{}_4]_2$ is exceptional when compared to the one of the related complexes with other anions. It is well soluble in acetone, CH_2Cl_2

and THF, although it is only slightly soluble in diethyl ether. On the contrary, the other complexes of the $[Pd(Phen)_2][X]_2$ type are only sparingly soluble in CH_2Cl_2, $CHCl_3$, $PhNO_2$ and DMSO and are essentially insoluble in all of the other solvents, including THF and acetone. This high solubility is a very important feature from the point of view of catalytic applications, since it considerably expands the range of solvents that can be employed with this kind of palladium-phenanthroline complexes.

Catalytic Reactions

General Trends

A few general trends can be highlighted before discussing the individual experiments.

a) Dinitrotoluene is very reactive and is generally completely consumed in the first part of the reaction, while nitrocarbamates (**2**) accumulate in solution.
b) As may be expected, the methyl group on the arene exerts a moderate steric hindrance on the adjacent nitro group and **2a** and **3a** are always more abundant in solution than **2b** and **3b**, respectively, although the ratio may be close to 1:1 in some cases.
c) Diaminotoluene **(5)** is also very reactive and is never detected at the end of the reaction even in those cases in which it was intentionally added to the reaction mixture since the beginning (see later).

Influence of the Addition of an Aniline

The first set of reactions was run under the same experimental conditions previously optimized by us for nitrobenzene as a substrate (Table 1). In the tables, the selectivity in total carbamates (**1** + **2a** + **2b** + **3a** + **3b**) is also reported. Compound **3b** was obtained with a selectivity < 1% in most cases and its exact quantification was often problematic. Its amount has been included in the total carbamates value only when a reproducible integration of its HPLC signal was observed.

From the data reported it immediately emerges that in the absence of any additive, the conversion is low even at a relatively low catalytic ratio and only trace amounts of dicarbamate are formed. We have previously shown[34,35] that the addition of aniline strongly accelerates the carbonylation reaction of nitrobenzene, especially at short reaction times. In the present system, addition of diaminotoluene also markedly improves the dinitrotoluene conversion, but the amount of dicarbamate remains low. Upon addition of phosphoric acid, however, larger amounts of **1** are formed. Increasing the catalytic ratio three-fold obviously results in a decreased conversion, which can however be raised by the addition of DMOP (2,2-dimethoxypropane) as an internal drying agent. A positive effect of DMOP has been previously reported in the literature for these types of reactions[20–24] and we also employed it in the case of nitrobenzene.[34,35] The catalytic ratio can further be doubled, provided the reaction time is also increased to 3 h.

Given the importance of the addition of an aniline, we investigated it more deeply. In the case of dinitrotoluene, three different amines can be added: **4a, b** and **5**. A comparison among them (Table 2) shows that **4b** is the most effective, as may be expected based on the observation that it is the least nucleophilic of the three, being deactivated by both electronic and steric effects. Indeed, if the rate determining step in the catalytic cycle involves the nucleophilic attack of an amine on a palladium complex, **4b** will be involved in the slowest reac-

Table 1. Effect of the addition of 2,4-diaminotoluene (**5**).[a]

Dinitrotol./Pd	Promoter	Promoter/Pd	**5**/Pd	DMPO [mL]	*t* [h]	Dinitrotol. conv. [%][b]	**1** sel. [%][c]	**2a** sel. [%][c]	**2b** sel. [%][c]	**3a** sel. [%][c]	Total carbamates[d]	**4a** sel. [%][c]	**4b** sel. [%][c]
450	–	–	–	–	1.5	53.3	0.2	18.7	14.4	–	33.3	< 1	16.7
450	–	–	50	–	1.5	98.0	10.0	13.9	7.9	0.8	32.6	1.1	15.3
450	H_3PO_4 85%	174	50	–	1.5	100	44.5	–	5.9	10.9	61.3	< 1	3.3
1350	H_3PO_4 85%	174	50	–	1.5	50.4	5.5	6.3	5.8	–	17.6	< 1	11.8
1350	H_3PO_4 85%	174	50	0.5	1.5	100	38.6	22.1	9.6	4.6	74.9	< 1	< 1
2700	H_3PO_4 85%	174	50	0.5	1.5	78.1	3.3	27.4	20.6	–	51.3	0.4	4.1
2700	H_3PO_4 85%	174	50	0.5	3	100	13.3	29.9	18.8	1.5	63.5	< 1	3.9
2700	H_3PO_4 85%	174	50	0.5	5	100	24.5	19.1	9.3	1.7	54.6	< 1	–
2700	H_3PO_4 85%	350	50	0.5	5	100	26.4	19.0	11.3	1.9	58.6	1.3	–

[a] Experimental conditions: catalyst $[Pd(Phen)_2][BF_4]_2 = 5.0$ mg, 7.8×10^{-3} mmol, mol ratio Phen/catalyst = 20, DMPO = 2,2-dimethoxypropane, $P_{CO} = 60$ bar, T = 170 °C, in methanol (10 mL). Conversion of **5** was complete in all cases. Selectivity in **3b** < 1%.

[b] Calculated with respect to the starting dinitrotoluene.

[c] Calculated with respect to the sum of reacted **5** and dinitrotoluene.

[d] Sum of the selectivities in **1**–**3**.

Table 2. Influence of the addition of **4a, b** and **5**.[a]

Amine	Amine conv. [%][b]	**1** sel. [%][c]	**2b** sel. [%][c]	**2a** sel. [%][c]	**3a** sel. [%][c]	Total carbamates[d]
5	100	26.4	11.3	19.0	1.9	58.6
4a	68.7	32.0	9.7	21.6	2.4	65.7
4b	~ 0[e]	52.6	12.4	22.5	2.4	89.9

[a] Experimental conditions: catalyst $[Pd(Phen)_2][BF_4]_2 = 5.0$ mg, 7.8×10^{-3} mmol, mol ratios 2,4-dinitrotoluene/added amine/H_3PO_4/Phen/Pd = 2700 : 50 : 350 : 20 : 1, 2,2-dimethoxypropane = 0.5 mL, $P_{CO} = 60$ bar, T = 170 °C, in methanol (10 mL), for 5 h. Conversion of dinitrotoluene was complete in all cases. Selectivity in **3b** < 1%. A very small amount (selectivity 0.9–1.3%) was observed for **4a, b** in those reactions in which they were not added since the beginning, but no **5** was ever detected at the end of the reaction.

[b] Calculated with respect to the starting amine.

[c] Calculated with respect to the sum of reacted amine and dinitrotoluene.

[d] Sum of the selectivities in **1**–**3**.

[e] The amount of **4b** at the end of the reaction was indistinguishable within the experimental error from the added one.

Table 3. Comparison of carboxylic and phosphorus acids.[a]

Dinitrotol./Pd	Promoter	**1** sel. [%][b]	**2a** sel. [%][b]	**2b** sel. [%][b]	**3a** sel. [%][b]	Total carbamates[c]	**4a** sel. [%][b]
365	PhCOOH	60.2	12.7	6.7	8.5	88.1	<1
365	85% H_3PO_4	71.1	5.9	<1	11.8	88.8	2.2
730	PhCOOH	35.1	27.7	15.9	2.7	81.4	<1
730	85% H_3PO_4	60.1	9.2	7.8	4.4	81.5	1.6
730	$PhPO(OH)_2$	80.5	<1	<1	<1	80.6	<1
1460	85% H_3PO_4	32.1	28.4	14.4	3.0	77.9	1.2
1460	$PhPO(OH)_2$	37.1	20.5	9.5	3.7	70.8	1.7

[a] Experimental conditions: catalyst $[Pd(Phen)_2][BF_4]_2 = 12.8$ mg, 0.020 mmol, mol ratios promoter/Phen/Pd = 100 : 4 : 1, 2,2-dimethoxypropane = 0.5 mL, $P_{CO} = 60$ bar, $T = 135$ °C, in methanol (10 mL), for 5 h. Conversion of dinitrotoluene was complete in all cases. A selectivity in **3b** and **4b** ≈ 1% was observed, but no **5** was ever detected.

[b] Calculated with respect to the starting dinitroarene.

[c] Sum of the selectivities in **1**–**3**.

tion in all the cycle. Since **4b** is both formed and consumed during the reaction, its concentration will reach a steady state anyway. However, the deliberate addition of more **4b** will alter the situation, resulting in a higher steady state concentration of this amine, thus increasing the rate of both the slow step and the global catalytic reaction.

Comparison with Other Experimental Conditions

Since the results were not fully satisfactory, we decided to test also the experimental conditions optimized by van Leeuwen for the related catalytic system promoted by carboxylic acids[18] (Table 3), although we also added DMOP, which had been shown to have a positive effect.

At the previously reported dinitroarene/Pd mol ratio of 365, both benzoic and phosphoric acid are effective, with the second affording a somewhat higher yield in dicarbamate. However, if the dinitrotoluene amount is doubled, the selectivity in **1** drops to 35% when benzoic acid is employed, while it only marginally falls to 60% in the case of phosphoric acid. An even better 80% selectivity is obtained with phenylphosphonic acid. The 60% selectivity in **1** is markedly higher than the one reported by van Leeuwen (31%) under very similar conditions,[18,44] but in the absence of 2,2-dimethoxypropane, and further highlights the importance of the addition of this dehydrating agent in the present system. However, even under these conditions doubling the dinitrotoluene amount causes a drop in the selectivity in **1**.

Optimization of the Amount of DMOP

Results concerning the optimization of the amount of DMOP are reported in Table 4.

The amount of **1** produced increases with the DMOP concentration up to a maximum and then decreases, but the total amount of carbamates increases steadily. This at first sight surprising behavior is due to the complex role water and anilines play in this catalytic system. An in-depth discussion of the reaction mechanism is outside the scope of this paper and only a brief descrip-

Table 4. Effect of the amount of DMOP.[a]

DMOP [mL]	**1** sel. [%][b]	**2a** sel. [%][b]	**2b** sel. [%][b]	**3a** sel. [%][b]	Total carbamates[c]	**4a** sel. [%][b]
–	16.1	23.9	15.0	1.5	56.5	<1
0.5	35.8	18.2	10.1	3.5	67.6	1.3
1	45.5	19.1	9.3	5.3	79.2	<1
2	36.9	27.9	18.2	6.0	86.0	<1

[a] Experimental conditions: catalyst $[Pd(Phen)_2][BF_4]_2 = 12.8$ mg, 0.020 mmol, mol ratios 2,4-dinitrotoluene/**4b**/85% H_3PO_4/Phen/Pd = 1460:50:110:4:1. The amount of **4b** at the end of the reaction was indistinguishable within the experimental error from the initially added one. $P_{CO} = 60$ bar, $T = 150\,°C$, in methanol (10 mL), for 5 h. Dinitrotoluene conversion was complete in all cases. A selectivity in **3b** $\approx$ 1% was observed, but no **5** was ever detected.

[b] Calculated with respect to the sum of reacted dinitrotoluene and **4b**.

[c] Sum of the selectivities in **1**–**3**.

tion of the reactions involved is given here. Studies conducted in our group on nitrobenzene as a substrate have shown that at least three mechanisms are operating at the same time, but under the normal operating conditions one strongly prevails.[45] In this mechanism nitrobenzene is intermediately reduced to aniline, which is in turn carbonylated to phenyl isocyanate, this step being rate-determining. When water is present, this can react with nitrobenzene and CO to afford aniline [Eq. (6)] and the increased steady state concentration of aniline causes a global rate increase in the catalytic reaction.

$$PhNO_2 + 2\,CO + H_2O \longrightarrow PhNH_2 + 2\,CO_2 \qquad (6)$$

During the reaction, water continuously reforms due to the hydrogen transfer reduction of nitrobenzene by the alcohol, a reaction which is slowest for methanol compared with other alcohols, but cannot be completely suppressed, Eq. (7).

$$CH_3OH + PhNO_2 \longrightarrow CH_2O + PhNO + H_2O \qquad (7)$$

However, it must also been considered that when the amount of aniline in solution increases too much, the selectivity in carbonylated products drops and large amounts of azoxybenzene are formed.[16,45] The reason for this change in selectivity is not known, but it may be simply related to the basicity of anilines. Indeed, it has been observed under various experimental conditions that the addition of any base, including weak bases such as carboxylates,[15] slows down the reaction and shifts it towards the formation of azo- and azoxyarenes, whereas acids increase both the rate of the reaction and the amount of carbonylated products. Thus it is clear that a moderate amount of water will lead to an amount of aniline in solution that is beneficial for the reaction rate, without compromising selectivity, but a larger amount will cause the aniline amount to increase too much, causing a decreased selectivity in carbamates. Since DMOP reacts with water in competition to the process in Eq. (6), the observed trend is exactly the one that may have been foreseen based on the preceding discussion and comes as no surprise. In particular, the low amount of **1** at high DMOP concentration is due to a slowing down of the reaction, which affects the second step in a more evident way, whereas the high selectivity in the formation of carbonylated products keeps the total carbamates amount very high.

Optimization of Other Experimental Conditions

Results concerning the optimization of the promoter, phenanthroline, solvent and **4b** amounts are reported in Table 5. The following points are worthy of comment:

a) Increasing the solvent amount from 10 to 20 or 30 mL improves both conversion of the intermediates **2** and selectivity in **1**, the best volume depending also on the amount of promoter. A rate increase upon dilution is not a common feature and is unlikely to be due to any kinetic law. However, Paul et al. have shown that when the carbonylation reaction of nitrobenzene catalyzed by palladium-phenanthroline complexes is run in neat nitrobenzene, several complexes form which are catalytically inactive.[26] It is possible that similar inactive complexes are formed in the case of dinitrotoluene when its concentration is too high.

b) As expected, the addition of **4b** increases rate and selectivity, but if too large amounts are added, selectivity in **1** decreases (entries 6, 8–11). This trend parallels, in the opposite sense, the effect of increasing amounts of DMOP and is clearly connected to this.

c) Use of 3,4,7,8-tetramethylphenanthroline as a ligand in place of unsubstituted phenanthroline gave worse results (runs 10 and 14). This is a bit surprising, since usually this substituted phenanthroline gives better results in carbonylation reactions of nitroarenes catalyzed by palladium. Since

Table 5. Effect of the amount of promoters under the conditions of Tables 3 and 4.[a]

Run	PhPO(OH)$_2$/Pd	**4b**/Pd	**4b** conv. [%][b]	**4b** sel. [%][c]	Phen/cat.	MeOH [mL]	**1** sel. [%][c]	**2a** sel. [%][c]	**2b** sel. [%][c]	**3a** sel. [%][c]	Total carbamates[d]	**4a** sel. [%][c]
1	110	50	≈0	–	4	10	47.3	22.4	12.6	4.8	87.1	<1
2	220	50	≈0	–	4	10	33.6	23.9	13.7	1.5	72.7	<1
3	220	50	38.4	–	8	20	60.8	16.3	6.7	4.5	88.3	<1
4	220	–	–	6.4	8	20	53.5	21.1	9.1	3.8	87.5	2.1
5	330	50	≈0	–	12	30	55.6	17.9	8.4	3.9	85.8	<1
6	165	50	≈0	–	12	30	56.1	15.5	6.9	4.6	83.1	<1
7	165	50	≈0	–	24	30	43.2	20.9	11.4	6.3	81.8	<1
8	165	–	–	5.0	12	30	53.0	20.1	9.6	4.2	86.9	<1
9	165	75	≈0	–	12	30	56.9	14.6	6.2	4.6	82.3	<1
10	165	100	22.6	–	12	30	62.9	12.1	5.3	5.1	85.4	<1
11	165	200	60.9	–	12	30	41.9	14.8	8.3	4.1	69.1	<1
12[e]	165	50	≈0	<1	12	30	53.9	21.4	9.9	4.9	90.1	<1
13[f]	165	100	57.3	–	12	30	66.9	7.9	5.7	4.7	85.2	2.1
14[g]	165	100	60.3	–	12	30	49.6	22.4	12.2	4.7	88.9	<1
15[h]	330	200	–	6.6	24	30	80.6	6.4	3.2	8.6	98.8	<1

[a] Experimental conditions: catalyst [Pd(Phen)$_2$][BF$_4$]$_2$ = 12.8 mg, 0.020 mmol, mol ratios 2,4-dinitrotoluene/Pd = 1460, DMOP = 1 mL, P_{CO} = 60 bar, T = 150 °C, in methanol (10 mL), for 5 h. In the cases where a conversion of **4b** ≈ 0 is indicated, its amount at the end of the reaction was indistinguishable within the experimental error from the initially added one. Dinitrotoluene conversion was complete in all cases. A selectivity in **3b** ≈ 1% was observed, but no **5** was ever detected.

[b] Calculated with respect to the initially added **4b**.

[c] Calculated with respect to the sum of reacted dinitrotoluene and **4b**.

[d] Sum of the selectivities in **1**–**3**.

[e] DMOP = 2 mL.

[f] t = 7 h.

[g] 3,4,7,8-Tetramethylphenanthroline was employed instead of Phen.

[h] [Pd(Phen)$_2$][BF$_4$]$_2$ = 6.4 mg, 0.010 mmol.

3,4,7,8-tetramethylphenanthroline is also much more expensive than phenanthroline, its use was not investigated further.

d) Halving both palladium and dinitrotoluene amounts, so that the same molar ratio is maintained, has a clear positive effect and a selectivity in **1** of 80.6% is reached (run 15). This effect is probably connected both to the nitroarene dilution effect discussed above and to the fact that palladium catalysts deactivate more slowly when the palladium concentration is low.

Effect of Other Acidic Promoters

At this stage, different phosphorus acids were tested (Table 6). The catalytic ratio was further increased in order to better differentiate among the various promoters. A comparison of the data in Table 6 shows that the introduction of an electron-donating group on the phenyl ring of phenylphosphonic acid results in a small increase in the amount of **1** formed, but the electron-withdrawing chloride slows down the reaction and larger amounts of the monocarbamates **2** are left unreacted. The positive effect of the methyl group is within the experimental error and it does not justify the use of this substituted acid, which is not commercially available and must be synthesized. Phosphoric acid and diphenylphosphinic acid were less effective.

Given the importance of reaching high selectivities while working at a high catalytic ratio, the amount of promoter, the temperature and the CO pressure were further varied while keeping the molar ratio dinitrotoluene/Pd = 2920 constant (Table 7). As for the carbonylation of nitrobenzene,[35] an increase in the CO pressure improves the carbamate yields (runs 1, 2 and 7, 8). The last entry of the table shows that the best result at this catalytic ratio (77.6% selectivity in **1**) was reached at 170 °C and 100 bar CO.

Other Attempts to Improve the Catalytic System

Several attempts were performed in the aim of further improving the efficiency of the catalytic system. They are briefly described here, although none of them resulted in a real improvement of the results.

a) Trimethyl orthoformate (TMOF) as the drying agent: Apart from 2,2-dimethoxypropane, trimethyl orthoformate is also a known internal drying agent, affording methyl formate and methanol by reaction with water, Eq. (8).

Table 6. Influence of the identity of the promoter.[a]

Promoter	**4b** conv. [%][b]	**1** sel. [%][c]	**2b** sel. [%][c]	**2a** sel. [%][c]	**3a** sel. [%][c]	Total carbamates[d]
$PhPO(OH)_2$	71.8	44.0	14.4	21.5	5.2	85.1
$4\text{-}CH_3C_6H_4PO(OH)_2$	56.8	45.8	9.8	18.9	4.9	79.4
$4\text{-}ClC_6H_4PO(OH)_2$	46.4	30.7	21.1	29.0	3.5	84.3
H_3PO_4 85%	28.5	30.0	20.2	26.2	6.5	82.9
H_3PO_4 100%	57.9	23.6	19.9	26.7	4.1	74.3
Ph_2POOH	53.3	28.9	20.4	27.0	3.7	80.0

[a] Experimental conditions: catalyst $[Pd(Phen)_2][BF_4]_2 = 3.2$ mg, 5.0×10^{-3} mmol, mol ratios 2,4-dinitrotoluene/**4b**/promoter/Phen/Pd = 2920:400:660:48:1, 2,2-dimethoxypropane = 1.0 mL, $P_{CO} = 60$ bar, $T = 150\,°C$, in methanol (30 mL), for 5 h. Conversion of dinitrotoluene was complete in all cases. Selectivity in **3b** and **4a** ≈ 1%.

[b] Calculated with respect to the starting amine.

[c] Calculated with respect to the sum of reacted **4b** and dinitrotoluene.

[d] Sum of the selectivities in **1**–**3**.

Table 7. Effect of CO pressure, $PhPO(OH)_2$ amount, and temperature.[a]

Run	**4b** conv. [%][b]	$PhPO(OH)_2/Pd$	T [°C]	P_{CO} [bar]	**1** sel. [%][c]	**2a** sel. [%][c]	**2b** sel. [%][c]	**3a** sel. [%][c]	Total carbamates[d]
1	71.8	660	150	60	44.0	21.5	14.4	5.2	85.1
2	51.5	660	150	80	51.8	14.9	7.5	5.8	80.0
3	88.2	330	150	80	46.8	16.0	8.8	6.3	77.9
4	59.2	495	150	80	59.5	11.7	6.1	7.3	84.6
5	54.3	495	170	80	70.0	6.3	5.8	5.3	87.4
6	54.0	495	180	80	67.5	9.5	8.3	4.4	89.7
7[e]	100	330	170	80	75.3	<1	<1	5.9	81.2
8[e]	100	330	170	100	77.6	1.1	–	2.6	82.1

[a] Experimental conditions: catalyst $[Pd(Phen)_2][BF_4]_2 = 3.2$ mg, 5.0×10^{-3} mmol, mol ratios 2,4-dinitrotoluene/**4b**/Phen/Pd = 2920:400:48:1, DMOP = 1.0 mL, in methanol (30 mL), for 5 h. Conversion of dinitrotoluene was complete in all cases. No **5** was observed. Selectivity in **3b** and **4a** ≈ 1%.

[b] Calculated with respect to the starting amine.

[c] Calculated with respect to the sum of reacted **4b** and dinitrotoluene.

[d] Sum of the selectivities in **1**–**3**.

[e] Methanol = 20 mL.

$$(MeO)_3CH + H_2O \longrightarrow MeOC(O)H + 2\,MeOH \qquad (8)$$

The effect of its addition in place of DMOP was investigated and the results are reported in Table S1, Supporting Information. A positive effect of small amounts of TMOF is evident and the amount of formate affording the best results is somewhat lower than the best DMOP amount (0.3 mL against 1.0 mL), which would be economically advantageous. However, overall the results obtainable with TMOF are clearly inferior to the ones realizable with the use of DMOP and its use was abandoned. It may be noted that at the end of the reactions to which TMOF was added, very low amounts of compounds containing the amino group were present. It should be considered that trialkyl orthoformates can react with amines directly and the reaction of **4b** with triethyl orthoformate to yield the corresponding Ar-N=C(H)OEt derivative has been reported in the literature.[46] Since the carbonylation reaction requires the presence of compounds containing the amino group to proceed, consumption of these by a side reaction is expected to slow down the reaction considerably. By comparison, it should also be recalled that even DMOP can react with amines and the reaction of 4-nitroaniline with DMOP to afford $4\text{-}O_2NC_6H_4N{=}C(CH_3)_2$ has been published.[47] However, Schiff bases derived from arylamines having electron-withdrawing substituents on the phenyl ring are well known to be hydrolyzed very easily and, accordingly, the amounts of the intermediates containing the amino group do not decrease when the amount of DMOP is increased (see the data in Table 4). The resistance to hydrolysis of compounds of the general formula Ar-N=C(H)OR has not been studied extensively and no comparison data are available with imines of related compositions. However, from general considerations it is clear that the mesomeric effect of the oxygen atom will make hydrolysis of these compounds more difficult than that of normal Schiff bases. This increased

Table 8. Effect of the modality of addition of **4b**.[a]

Run	**4b** conv. [%][b]	t [h]	**1** sel. [%][c]	**2a** sel. [%][c]	**2b** sel. [%][c]	**3a** sel. [%][c]	Total carbamates[d]
1[e]	56.0	2+3	46.9	17.8	9.8	6.2	80.7
2[f]	49.7	2+3	30.4	27.1	17.9	4.9	80.3
3[g]	51.9	2+3	54.3	13.1	6.6	6.0	80.0

[a] Experimental conditions: catalyst $[Pd(Phen)_2][BF_4]_2 = 3.2$ mg, 5.0×10^{-3} mmol, mol ratios 2,4-dinitrotoluene/**4b**/$PhPO(OH)_2$/Phen/Pd = 2920:660:400:48:1, DMOP = 1.0 mL, $P_{CO} = 80$ bar, $T = 150$ °C, in methanol (30 mL), for 5 h. Conversion of dinitrotoluene was complete in all cases. No **5** was observed. Selectivity in **3b** and **4a** ≈ 1%.

[b] Calculated with respect to the starting amine.

[c] Calculated with respect to the sum of reacted **4b** and dinitrotoluene.

[d] Sum of the selectivities in **1**–**3**.

[e] Half of the amount of **4b** was added at the beginning of the reaction and half after 2 h.

[f] All **4b** was added after the reaction had been run for 2 h.

[g] All **4b** was added at the beginning, but the reaction was anyway stopped and CO vented and recharged as for the first two reactions in the table.

difficulty in hydrolysis can explain both the very low amount of compounds containing the amino group at the end of the reactions where TMOF had been added and the inhibiting effect of even relatively small amounts of it.

*b) Mode of addition of **4b**:* We have previously mentioned that mechanistic studies in progress in our laboratories, employing nitrobenzene as substrate, indicate that the principal mechanism for the reaction requires the intermediate reduction of nitrobenzene to aniline, which is only later carbonylated. Such a mechanism has several precedents[1] and is characterized by the fact that the amount of aniline consumed equals that formed from nitrobenzene, so that any excess of aniline added to the reaction mixture will remain approximately constant during the reaction. However, a second stoichiometry for the carbonylation of nitroarenes [Eq. (9)] is also possible as an alternative to the one described by Eq. (1). Such a process has been found to be operative in several cases with palladium catalysts[1,19] and we have also recently shown that it plays an important role even in the presence of some ruthenium catalysts.[48] When a process associated with this stoichiometry is operative, the additional aniline is irreversibly consumed, Eq. (9).

$$ArNO_2 + 2\,ArNH_2 + 3\,CO + 3\,MeOH \longrightarrow 3\,ArNHC(O)OMe + 2\,H_2O \tag{9}$$

At least in the case of the carbonylation of nitrobenzene, the mechanistic studies in our group show that this stoichiometry does indeed play a role under certain experimental conditions, but is almost absent in the presence of acidic promoters. In the case of dinitrotoluene, however, the contribution of this reaction stoichiometry to the overall process is not known and cannot be excluded *a priori*. If such a process is occurring, then the amount of **4b** initially added will decrease during the reaction and the overall process will slow down. We have thus investigated the effect of adding **4b** at different moments. To this purpose, a reaction was run in which half of the standard amount of **4b** was initially added. The reaction was run for 2 h, after which it was stopped, the autoclave vented and the remaining aliquot of amine added. The reaction was then run for additional 3 h (Table 8, run 1). Two comparison reactions were run with the same procedure. In the first (Table 8, run 2) all of **4b** was added after the first 2 hours, whereas in the second (run 3) all **4b** was added at the beginning of the reaction. A comparison is also worthwhile with the results of entry 2 in Table 7, which is run under the same experimental conditions, but with no interruption. Clearly there is no advantage in adding the amine stepwise and the best results are obtained when the amine is added all at once at the beginning. Stopping the reaction and recharging CO appears to give a small increase in the amount of **1** formed (from 51.8 to 54.3%), which is in line with the better results generally obtained when working at higher CO pressures. Thus irreversible consumption of **4b** by a reaction of the kind of that reported in Eq. (9) does not appear to play a relevant role at least under the actual reaction conditions.

c) Presence of a second metal: In the literature, it has been reported that the addition of azo- or azoxybenzene to the reaction mixture retards the carbonylation reaction of nitrobenzene by palladium-phenanthroline catalysts. The addition of silver, copper or mercury salts was said to restore the initial activity.[23] In the case of dinitrotoluene, numerous azo and azoxy derivatives are possible and it is not obvious what their individual effects may be. At least under our reaction conditions, the deliberate addition of up to 5 mol % azo- or azoxybenzene with respect to the starting dinitrotoluene did not result in any significant change in rate or selectivity. However, since other, possibly more noxious, azo derivatives can be formed from dinitrotoluene, we tested in any case the effect of the presence of silver triflate or copper acetate,

Table 9. Experiments run under CO + CO_2 pressure.[a]

Run	**4b** conv. [%][b]	Dinitrotol. conv. [%][c]	P_{CO_2} [bar]	*t* [h]	**1** sel. [%][c]	**2a** sel. [%][d]	**2b** sel. [%][d]	**3a** sel. [%][d]	Total carbamates[e]	**4a** sel. [%][d]
1[f]	100	100	10	5	68.8	2.5	1.9	1.9	75.1	<1
2	100	100	–	5	71.7	2.2	4.5	2.3	80.7	<1
3	51.0	76.7	10	1	2.9	37.4	34.0	<1	74.3	2.3
4	46.7	85.8	–	1	2.7	37.3	30.5	<1	70.5	2.1

[a] Experimental conditions: catalyst $[Pd(Phen)_2][BF_4]_2 = 3.2$ mg, 5.0×10^{-3} mmol, mol ratios 2,4-dinitrotoluene/$PhPO(OH)_2$/**4b**/Phen/Pd = 2920 : 330 : 400 : 32 : 1, DMOP = 1.0 mL, $P_{CO} = 80$ bar, $T = 170\,°C$, in methanol (20 mL). Selectivity in **3b** <1%. No **5** was observed after runs 2–4.

[b] Calculated with respect to the starting **4b**.

[c] Calculated with respect to the starting dinitrotoluene.

[d] Calculated with respect to the sum of reacted **4b** and dinitrotoluene.

[e] Sum of the selectivities in **1**–**3**.

[f] A small amount (sel. 0.8%) of **5** was formed.

two of the best promoters according to the literature. The results (Table S2, Supporting Information), however, show that under our experimental conditions the presence of this second metal always depresses the reaction, rather than promoting it. The effect is larger when the amount of metal is increased.

d) Effect of CO_2: Carbonic anhydride is formed during the reaction and may influence the reactivity. Specifically, it is well known that amines react with CO_2 to afford carbamate salts, Eq. (10).

$$2\,ArNH_2 + CO_2 \rightleftharpoons [ArNHCOO]^- [ArNH_3]^+ \qquad (10)$$

It has been shown that the formation of the carbamate salts plays an important and beneficial role in the synthesis of methyl phenylcarbamate by reaction of aniline and dimethyl carbonate,[49] the effect being due to the higher nucleophilicity of the carbamate ion with respect to aniline. We have no evidence for dimethyl carbonate formation under our experimental conditions, but a nucleophilic attack of an arylamine on an intermediate palladium complex is surely a key step of the catalytic cycle and formation of carbamate salts may influence it. We thus investigated the effect of charging 10 bar CO_2 from the beginning of the reaction. Only a slightly negative effect is observable (Table 9). Especially significant are the experiments run for a short reaction time, where any effect of CO_2 should be enhanced since little CO_2 has at that time been produced by the reduction reaction itself.

Without questioning the importance of carbamate salts formation when the reactions in the presence of dimethyl carbonate are performed, we note that the temperature at which our reaction is run is much higher. Although we do not have precise thermodynamic data, the reaction in Eq. (10) consumes one equivalent of a gaseous compound and produces ionic products from neutral reagents. Thus it is surely associated with a strongly negative ΔS and is disfavored by high temperatures. The reported results suggest that the equilibrium is almost completely shifted to the left side in the case of the reactions (and the experimental conditions) studied in this paper.

e) Effect of the counteranion: It is well known that the counteranion of $[Pd(Phen)_2]^{2+}$ must be non-interacting for maximum activity to be observed. However, it should also be very stable if the catalyst is to remain active for prolonged periods of time. During our studies, we have mostly employed BF_4^- as a counteranion. We had earlier tested PF_6^- with nitrobenzene as a substrate and found it to afford slightly worse results, despite the fact that Mestroni and co-workers found it to be a little superior to BF_4^- with the same catalytic system, but under different experimental conditions.[7] In this work, we decided to try two different counteranions, the use of which in association with the palladium-phenanthroline system has not been reported before: SbF_6^- and $BAr^F{}_4^-$. The former is known for its remarkable chemical stability, whereas the second is among the least interacting anions known. The synthesis of the two corresponding complexes is described earlier in this paper. A comparison between the results obtained with these complexes and with the "standard" BF_4^- complex is reported in Table 10. The use of $[Pd(Phen)_2][SbF_6]_2$ as catalyst gives results which perfectly match those obtainable with the BF_4^- salt, whereas the one of $BAr^F{}_4^-$ affords a slightly poorer performance.

The almost identity of the results obtained with the BF_4^- and SbF_6^- complexes indicates that no specific decomposition of BF_4^- can be responsible for the catalyst deactivation that is discussed later.

The lower amount of **1** formed with the last catalyst is unlikely to be due to an intrinsically lower reactivity of the $BAr^F{}_4^-$ compound and it is possible that a faster deactivation is occurring in this case. Indeed, despite the

Table 10. Effect of the counteranion.[a]

4b conv. [%][b]	Anion	**1** sel. [%][c]	**2a** sel. [%][c]	**2b** sel. [%][c]	**3a** sel. [%][c]	**3b** sel. [%][c]	Total carbamates[d]
100	BF_4^-	68.1	1.4	2.6	2.3	0.8	75.2
100	SbF_6^-	68.2	3.2	3.4	2.4	0.7	77.9
100	$BAr^F_4{}^-$	63.5	3.3	3.7	2.2	0.7	73.4

[a] Experimental conditions: catalyst $[Pd(Phen)_2][BF_4]_2 = 3.2$ mg, 5.0×10^{-3} mmol, mol ratios 2,4-dinitrotoluene/**4b**/$PhPO(OH)_2$/Phen/Pd = 2920:330:400:32:1, DMOP = 1.0 mL, $P_{CO} = 100$ bar, $T = 170$ °C, in methanol (20 mL), for 3.5 h. Conversion of dinitrotoluene was complete in all cases. No **5** was observed. Selectivity in **4a** < 0.5%.

[b] Calculated with respect to the starting amine.

[c] Calculated with respect to the sum of reacted **4b** and dinitrotoluene.

[d] Sum of the selectivities in **1**–**3**.

fact that the fluorinated substituents impart a much better stability towards the breaking of the B–C bond with respect to the unsubstituted BPh_4^-, a decomposition reaction of this derivative has been reported in the literature,[50] which occurs under conditions that are milder than those employed in the present reaction.

f) Addition of benzoquinone: The palladium complex employed in this paper is also commonly employed to catalyze another reaction, namely the styrene-CO copolymerization.[41] This reaction shares with the one investigated here the presence of an alcohol as solvent and the use of CO, although the olefin and nitroarene clearly differentiate the two. Under co-polymerization conditions, it has been shown that a major path for catalyst deactivation is due to palladium hydride formation, which then evolves to inactive compounds.[51] This deactivation can be avoided by the addition of benzoquinone, which oxidizes the palladium hydride complex. In the present reaction, an oxidant is already present, the nitroarene, but it is not clear how efficient it will be in scavenging possible palladium hydride complexes. We thus investigated the addition to the reaction mixture of variable amounts of benzoquinone (Table S3, Supporting Information). Under the usual operational conditions, no effect of the presence of benzoquinone is detectable even when it is added in a large amount

Table 11. Catalyst deactivation.[a]

Run	Cat. amount [$10^{-3} \times$ mmol]	Dinitrotol./Pd	$PhPO(OH)_2$/Pd	**4b** conv. [%][b]	**4b**/Pd	Phen/Pd	T [°C]	t [h]	**1** sel. [%][c]	**2a** sel. [%][c]	**2b** sel. [%][c]	**3a** sel. [%][c]	Total carbamates[d]
1	5.0	2920	495	25.9	400	48	170	1	2.4	36.8	35.0	2.4	76.6
2	5.0	2920	495	55.9	400	48	170	2	16.5	33.6	26.8	2.9	79.8
3	5.0	2920	495	77.7	400	48	170	3.5	64.0	10.2	7.3	6.8	88.3
4	5.0	2920	495	54.3	400	48	170	5	70.0	6.3	5.8	5.3	87.4
5	5.0	2920	495	100	400	48	170	7	69.3	3.8	9.4	4.9	87.4
6	2.5	5840	990	38.1	800	96	170	3.5	7.2	30.5	29.9	0.9	68.5
7	2.5	5840	990	84	800	96	170	5	33.8	21.3	14.6	3.3	73.0
8	2.5	5840	990	87.3	800	96	170	7	32.6	20.6	13.5	2.4	69.1
9	5.0	2920	660	51.5	400	48	150	5	51.8	14.9	7.5	5.8	80.0
10[e]	5.0	2920 × 2	660	29.4	400 × 2	48	150	5 + 5	39.1	12.7	12.2	0.7	64.7
11[f]	5.0	2920 × 3	660	100	400	48	170	1 + 1 + 7	24.9	23.3	14.8	0.6	64.1
12[g]	5.0 + 5.0	(2920)	(495)	100	(400)	(48)	170	3.5 + 1.5	68.0	3.7	3.9	5.9	81.5
13[h]	5.0	2920	495 × 2	100	400	48	170	3.5 + 1.5	60.9	3.3	< 1	3.4	67.6

[a] Experimental conditions: catalyst $[Pd(Phen)_2][BF_4]_2$, DMOP = 1.0 mL, $P_{CO} = 100$ bar, in methanol (20 mL). Conversion of dinitrotoluene was complete in all cases. No **5** was observed. Selectivity in **3b** and **4a** ≈ 1%. In the cases in which the catalytic solution was recycled, the results reported refers to the finally obtained amounts.

[b] Calculated with respect to the added **4b**.

[c] Calculated with respect to the sum of reacted **4b** and dinitrotoluene.

[d] Sum of the selectivities in **1**–**3**. [e] After a standard reaction, more dinitrotoluene and **4b** were charged, in amounts equal to the initial ones, and the reaction was repeated.

[f] The catalytic solution was recycled two more times, by adding only dinitrotoluene after the first two runs.

[g] After 3.5 h the reaction was stopped and more catalyst (5.0×10^{-3} mmol) added, before running the reaction for a further 1.5 h. The ratios in parentheses refer to the initial amount of catalyst.

[h] After 3.5 h the reaction was stopped and more $PhPO(OH)_2$ was added, before running the reaction for a further 1.5 h.

(runs 1–4). At a short reaction time, a small inhibiting effect is even present (runs 5 and 6), but, at a higher catalytic ratio, dinitrotoluene/Pd = 5840, and for a long reaction time a positive effect is observed (runs 7 and 8). However, it was also noticed that when large amounts of benzoquinone are added, the solution becomes viscous during the reaction and some polymerization is clearly occurring that will make work-up more difficult. Thus addition of benzoquinone is not a viable way of improving the performances of the catalytic system for the carbonylation of dinitrotoluene.

In any case, it should be noted that a catalytic ratio dinitrotoluene/Pd = 5840 is by far the highest reported in the literature for this reaction. The highest ratio previously reported (at least in the free literature) is 500.[24]

Catalyst Deactivation

To test the stability of the catalytic system, the products amounts were investigated as a function of reaction time. The results in runs 1–5 of Table 11 show that the catalytic reaction proceeds for the first five hours, but increasing the reaction time by two more hours has no effect, in spite of the fact that unreacted **2** and **3** are still present (see also Figure 1). It should be noted that the low amount of **1** formed in the first hour does not imply that an induction time is present. It is simply due to the two-steps nature of the reaction itself and the previously mentioned fact that carbonylation of **2** only begins when almost all dinitrotoluene has reacted.

Worthy of note is that the very reactive dinitrotoluene was completely consumed in the first reaction hour and was not present at the end even of the first reaction of the series. When the catalyst amount was halved, catalyst deactivation occurred in approximately the same time (Table 11, runs 6–8; Figure 1) and about half of the amount of **1** was formed with respect to that obtained with the standard amount of catalyst.

Adding more dinitrotoluene and **4b** to the solution after a reaction results in a decreased amount of **1** (runs 9 and 10), but dinitrotoluene was anyway completely consumed and, noteworthy, complete dinitrotoluene conversion was observed even when the same solution was recycled two times, with no other addition apart from dinitrotoluene and, inevitably, CO (run 11).

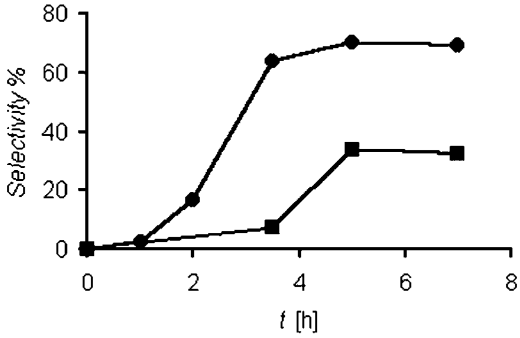


Figure 1. Selectivity in **1** as a function of reaction time. Catalyst = 5.0×10^{-3} mmol (circles), catalyst = 2.5×10^{-3} mmol (squares). Data in Table 11.

Two more experiments were also performed, in which the reaction was stopped after 3.5 h and a further aliquot of either the catalyst (run 12) or phenylphosphonic acid (run 13) was added before running the reaction for a further 1.5 h. A comparison with the data for entry 4 in the table, which was run for 5 h continuously without any addition, shows that there is no improvement in effecting either of the additions. The addition of more acid even decreased the amount of **1** produced, which confirms that the initially added amount is close to the optimal value.

We recall that when nitrobenzene is employed as substrate, no catalyst deactivation was observed up to 10^5 turnovers. To test if an intrinsically much lower reactivity of **2** with respect to nitrobenzene was responsible for the slowing down of the reaction rate, a reaction was run under the same experimental conditions of entry 6 in Table 11, but for only 1 h, employing a mixture of nitrobenzene and **2b** (2920 times each with respect to palladium). At the end of the reaction, 61.7% of nitrobenzene and 43.8% of **2b** had been converted. Thus nitrocarbamates are indeed less reactive than nitrobenzene, but the difference is small and is unlikely to be responsible for any major deactivation pathway.

Taken together, the results of these experiments imply that:

a) Catalyst deactivation is neither due to palladium black formation (which is indeed not visually observed, although the very small amount of palladium present may render its detection problematic) nor to the formation of large inactive metal clusters. Indeed, decreasing the palladium concentration generally affords higher turnover numbers when its aggregation is the cause for catalyst deactivation. Moreover, addition of fresh catalyst after 3.5 h does not restore the initial catalytic activity.
b) Deactivation is not due to amine consumption, a result also in line with the results of the reactions in which **4b** was not added all at the beginning of the reaction (Table 8).
c) Even a consumption of the acidic promoter is not involved in the deactivation. We have previously reported that esterification of phenylphosphonic acid only occurs to a limited extent under the reaction conditions.[34, 35]

At this stage, the most likely explanation for the observed deactivation is that some organic compounds are formed during the reaction which interact with the palladium catalyst and decrease its reactivity. Azo- and azoxyarenes have been reported to have an inhibiting effect on these reactions, but, as already discussed earlier in this paper, azo- and azoxybenzene do not deactivate the catalyst under the conditions of this study. Whether any of the azo- or azoxy compounds which can be formed from dinitrotoluene can deactivate the catalyst more efficiently remains an open question. In any case, the remedy suggested in the literature, addition of a silver or copper salt, is ineffective under the present conditions.

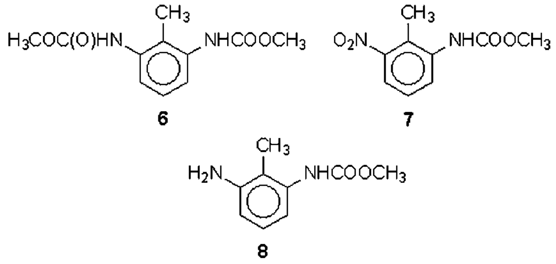
Whichever the cause, it must be stressed that the deactivation is only partial. Indeed the data clearly show that the "deactivated" catalyst is still able to carbonylate the very reactive dinitrotoluene to yield **2** (complete conversion of the starting material is observed even in run 11, where the ratio dinitrotoluene/Pd = 8760), but it is no longer active enough to react with **2**.

Separation of 1 from the Reaction Mixture

Easy separation of the reaction product is an important issue for an industrial process. In the actual technology, the diisocyanate is purified by distillation, which is not feasible in the case of the dicarbamate. Fortunately, **1** is poorly soluble in methanol at room temperature. To test the efficiency of a separation based on this property, a reaction was run under the conditions of the last entry in Table 7. At the end of the reaction, the glass liner (see Experimental Section) was cooled down to 0 °C and, after 1 h, the precipitate was filtered off. HPLC analysis of the solid showed it to be 90% pure **1** (52.7% yield, calculated on the pure product), contaminated by **2a** and **2b**. No phenanthroline or phosphorus-containing products could be detected by NMR even in very concentrated solutions. A single recrystallization of the solid from methanol afforded **1** with 98.8% purity. Since the remaining catalytic solution is now saturated with **1**, it is expected that further recycling should afford even higher yields of isolated product, although we did not test this aspect in any more detail. The methanol employed in the recrystallization may easily be recycled as the reaction solvent, taking into consideration that some methanol is also consumed as a reactant during the process. The co-precipitated **2a** and **2b** would also be recycled by this procedure. Thus an easy and selective separation of the product is possible.

Use of 2,6-Dinitrotoluene as Feedstock

Finally, it must be considered that the dinitrotoluene employed as feedstock in the industrial process contains *ca.* 10% of the 2,6-isomer and this also needs to be carbonylated efficiently in order for the process to be commercially viable. This compound (Scheme 3) is the most difficult to carbonylate, since both nitro groups are in a sterically hindered position. To the best of our knowledge, only one report has appeared in the open literature describing its carbonylation to the corresponding dicarbamate,[52] and only a 30% yield was obtained although the catalytic ratio was low [$PtCl_2(PPh_3)_2$ 1 mol %, $FeCl_3$ 20 mol %]. By carbonylating 2,6-dinitrotoluene under the same conditions of the last entry in Table 7 (but employing 2-nitro-6-aminotoluene in place of **4b**) we observed complete conversion of the dinitroarene and obtained the desired dicarbamate, **6** with 73.5% selectivity, only slightly lower than the one obtainable with the 2,4-isomer, accompanied by **7** (5.1%) and **8** (9.9%). Since **6** is less soluble in methanol than **1**, its separation from the reaction solution should be even easier in an industrial process. Analogously to the case of **2** and **3**, an independent synthesis of **7** and **8** has not been reported in the literature. We obtained them by the same technique employed for **2** and **3b**, respectively (see the Experimental Section for details). A pure sample of **6** was best obtained by crystallization of the solid precipitated after a catalytic reaction.



Scheme 3. Numbering scheme for the products derived from 2,6-dinitrotoluene.

Conclusions

In conclusion, we have shown that phosphorus acids are not only excellent promoters for the palladium-phenanthroline-catalyzed carbonylation of nitrobenzene, but the strongly positive effect also extends to the difficult but economically important dinitrotoluenes and activities and selectivities very close to the limits for commercial applicability have been reached for the first time.

Experimental section

General Procedure

All solvents were dried by standard procedures, distilled and stored under dinitrogen before use. Reactions were generally conducted under a dinitrogen atmosphere, with standard Schlenk and cannula techniques (for catalytic reactions see the dedicated paragraph). However, the exchange reactions between $[Pd(Phen)_2][NO_3]_2$ and $NaSbF_6$ and the synthesis of [PhenH][Cl] can be conducted in the air. Phenanthroline monohydrate was dried by dissolving it in CH_2Cl_2 and drying the resulting solution with Na_2SO_4. The solution was then filtered, evaporated under vacuum, and the obtained phenanthroline was stored under a dinitrogen atmosphere. Dry Phen can be quickly weighed in the air without problems, but long storing in an undried atmosphere converts it quantitatively to the monohydrate. $[Pd(Phen)_2][BF_4]_2$,[7] $[Pd(Phen)_2][NO_3]_2$,[7] and $NaBAr^F_4$[42,43] were synthesized as reported in the literature. For the last compound, a slight modification of the two reported procedures, taking the advantages of both, was employed. Phenanthrolinium chloride monohydrate was prepared by adding the stoichiometric amount of 36% HCl to a toluene solution of dry phenanthroline (phenanthroline monohydrate is poorly soluble in toluene) and was isolated by filtration. Inclusion of one molecule of water per molecule of phenanthrolinium chlorohydrate was evidenced by both ^1H NMR and elemental analysis. Use of gaseous HCl in this reaction to avoid the co-crystallization of water is not advisable, since a mixture of mono- and dichlorohydrate (with the second prevailing) was obtained with this reagent. $4\text{-}MeC_6H_4P(O)(OH)_2$ and $4\text{-}ClC_6H_4P(O)(OH)_2$ were synthesized by reaction of triethyl phosphite with $4\text{-}MeC_6H_4Br$ and $4\text{-}ClC_6H_4Br$, respectively, in the presence of $NiBr_2$, following the method of Tavs,[53] followed by hydrolysis of the ester with 37% HCl as reported.[54] They were characterized by comparison of their analytical data with those reported in the literature.[55] 2,4-Dinitrotoluene was recrystallized from methanol to remove the water present in the commercial product. The anhydrous product was stored under dinitrogen. Compounds **4a**, **b** and **5** were purified by sublimation. The diamine **5** was then stored under dinitrogen, whereas **4a**, **b** can be stored in the air. All other reagents except for those mentioned in the following were commercial products and were employed as received. IR spectra were recorded on a Bio-Rad FTS-7 spectrophotometer; ^1H NMR spectra were recorded on a Bruker DPX 300 (300 MHz) spectrometer; elemental analyses were performed in the analytical laboratories of the Milan University. HPLC analyses were performed on a Hewlett Packard series 1050 chromatograph. Gas chromatographic analyses were performed on a Dani 8610 capillary gas chromatograph (see later for details of the analysis conditions).

Synthesis of $[Pd(Phen)_2][SbF_6]_2$

The procedure is adapted from ref.[7] To a flask were added $[Pd(Phen)_2][NO_3]_2$ (300 mg, 0.51 mmol), $NaSbF_6$ (527.7 mg, 2.04 mmol) and methanol (30 mL). The suspension was stirred at room temperature for 2 h, after which the pale yellow solid was collected by filtration, washed with methanol and dried under vacuum; yield: 384 mg (79.9%). The solid was pure from residual nitrate ion, as evidenced by the lack of nitrate absorptions at 825 and 667 cm^{-1} in its IR spectrum (in nujol), while the new absorptions at 884 and 653 cm^{-1} due to SbF_6^- were present. Elemental analysis: calcd. for $C_{20}H_{16}N_4F_{12}PdSb_2$: C 30.72, H 1.72, N 5.97%; found: C 30.57, H 1.73, N 6.00%.

Synthesis of $[PhenH][BAr^F_4]$

To a Schlenk flash under a dinitrogen atmosphere were added $[PhenH][Cl]\cdot H_2O$ (179.8 mg, 0.766 mmol) and $NaBAr^F_4$ (679.6 mg, 0.766 mmol). The reagents were dissolved in the minimum amount of methanol (~ 5 mL) and the solution stirred for 30 min, after which it was evaporated under vacuum. Treatment of the residue with diethyl ether left NaCl as a solid residue, which was filtered off. Evaporation of the ether solution under vacuum afforded the crude yellowish product, which was purified by the Soxhlet extraction of the impurities with hexane for 10 h, to afford the colorless analytically pure $[PhenH][BAr^F_4]$; yield: 600 mg (75%). The compound was shown to be free from chloride impurities by the Ag^+ test. Elemental analysis: calcd. for $C_{42}H_{21}N_2BF_{24}$: C 50.60, H 2.03, N 2.68; found: C 50.64, H 1.73 N 2.73; ^1H NMR (CD_3COCD_3): $\delta = 9.44$ (dd, $J_{2,3} = 4.9$, $J_{2,4} = 1.3$ Hz, 2H, H2, H9), 9.09 (dd, $J_{4,3} = 8.3$, $J_{4,2} = 1.3$ Hz, 2H, H4, H7), 8.40 (s, 2H, H5, H6), 8.80 (dd, $J_{3,2} = 4.9$, $J_{3,4} = 8.3$ Hz, 2H, H3, H8), 7.80 [t(br), $J_{1H,11B} =$ 2.3 Hz, 8H, H_{ortho} Ar^F], 7.68 (s, 4H, H_{para} Ar^F).

Synthesis of $[Pd(Phen)_2][BAr^F_4]_2$

$Pd(OAc)_2$ (19.4 mg, 0.086 mmol) and $[PhenH][BAr^F_4]$ (180.1 mg, 0.172 mmol) were separately dissolved in acetone (~ 2.5 mL for each). The palladium acetate solution was filtered through filter paper with the aid of a cannula to remove very small amounts of insoluble impurities and added to the phenanthrolinium solution. After stirring at room temperature for 2 h the still homogeneous solution was evaporated under vacuum and the resulting sticky solid treated with hexane (3 mL). After stirring the suspension at room temperature overnight the solid residue was collected by filtration and washed with more hexane (2 mL) to give the analytically pure product; yield: 265 mg (70%). Elemental analysis: calcd. (%) for $C_{84}H_{40}N_4B_2F_{48}Pd$: C 48.19, H 1.84, N 2.55; found: C 48.46, H 1.86, N 2.48; ^1H NMR (CD_3COCD_3): $\delta = 9.34$ (dd, $J_{2,3} = 5.0$, $J_{2,4} = 1.2$ Hz, 4H, H2, H9), 8.99 (dd, $J_{4,3} = 8.2$, $J_{4,2} =$ 1.2 Hz, 4H, H4, H7), 8.39 (s, 4H, H5, H6), 8.07 (dd, $J_{3,2} = 5.0$, $J_{3,4} = 8.2$ Hz, 4H, H3, H8), 7.79 [t(br), 16H, H_{ortho} Ar_F], 7.67 (s, 8H, H_{para} Ar^F).

Catalytic Reactions

In a typical catalytic reaction, the catalyst, Phen, dinitrotoluene, and, when required, an amine (**4a**, **4b**, or **5**) and the acidic promoter were weighed in a glass liner. The liner was placed inside a Schlenk tube with a wide mouth under dinitrogen and was frozen at −78 °C with dry ice, evacuated and filled with dinitrogen, after which the solvent was added. After the solvent was also frozen, the liner was closed with a screw cap having a glass wool-filled open mouth which allows gaseous reagents to exchange and rapidly transferred to a 200-mL stainless steel autoclave with magnetic stirring. The autoclave was then evacuated and filled with dinitrogen three times. CO was then charged at room temperature at the required pressure and the autoclave was immersed in an oil bath preheated at the required temperature; the autoclave took about 15 min to fully equilibrate at the final temperature. Other experimental conditions are reported in the captions to the tables and figures. At the end of the reaction the autoclave was cooled with an ice bath and vented. The products were analyzed by HPLC (RP-18 column, methanol/water 55:45 as eluent, benzophenone as the internal standard; for 2,4- and 2,6-dinitrotoluene,

1, **2a, b**, **3a, b**, **6**, **7**, and **8**) and gas chromatography (PS 255 column, naphthalene as the internal standard; for **4a, b** and **5**).

Supporting Information Available

Tables S1-S3; experimental details for the synthesis of compounds **1–8** and their characterization data.

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References and Notes

[1] S. Cenini, F. Ragaini, *Catalytic Reductive Carbonylation of Organic Nitro Compounds*, Kluwer Academic Press, Dordrecht, **1997**, and references cited therein.
[2] F. Paul, *Coord. Chem. Rev.* **2000**, *20*, 269–323, and references cited therein.
[3] A. M. Tafesh, J. Weiguny, *Chem. Rev.* **1996**, *96*, 2035–2052, and references cited therein.
[4] E. Drent, P. W. N. M. Van Leeuwen, *US Patent* 4,474,978, **1984**; *Eur. Pat. Appl.* EP 86,281, **1983**; *Chem. Abstr.* **1984**, *100*, 6109x.
[5] E. Drent, *Eur. Pat. Appl.* EP 231,045, **1987**; *Chem. Abstr.* **1988**, *109*, 128605n.
[6] J. Stapersma, K. Steernberg, *Eur. Pat. Appl.* EP 296,686, **1988**; *Chem. Abstr.* **1989**, *111*, 133802v.
[7] A. Bontempi, E. Alessio, G. Chanos, G. Mestroni, *J. Mol. Catal.* **1987**, *42*, 67–80.
[8] E. Alessio, G. Mestroni, *J. Mol. Catal.* **1984**, *26*, 337–340.
[9] E. Alessio, G. Mestroni, *J. Organomet. Chem.* **1985**, *291*, 117–127.
[10] E. Drent, *Pure Appl. Chem.* **1990**, *62*, 661–9.
[11] S. Cenini, F. Ragaini, M. Pizzotti, F. Porta, G. Mestroni, E. Alessio, *J. Mol. Catal.* **1991**, *64,* 179–190.
[12] P. Leconte, F. Metz, *Eur. Pat. Appl.* EP 330,591, **1989**; *Chem. Abstr.* **1990**, *112*, 78160c.
[13] P. Wehman, G. C. Dol, E. R. Moorman, P. C. J. Kamer, P. W. N. M. van Leeuwen, J. Fraanje, K. Goubitz, *Organometallics* **1994**, *13*, 4856–4869.
[14] P. Wehman, V. E. Kaasjager, W. G. J. de Lange, F. Hartl, P. C. J. Kamer, P. W. N. M. van Leeuwen, J. Fraanje, K. Goubitz, *Organometallics* **1995**, *14*, 3751–3761.
[15] P. Wehman, L. Borst, P. C. J. Kamer, P. W. N. M. van Leeuwen, *J. Mol. Catal. A* **1996**, *112*, 23–36.
[16] P. Wehman, L. Borst, P. C. J. Kamer, P. W. N. M. van Leeuwen, *Chem. Ber./Recueil* **1997**, *130*, 13–21.
[17] P. Wehman, H. M. A. van Donge, A. Hagos, P. C. J. Kamer, P. W. N. M. van Leeuwen, *J. Organomet. Chem.* **1997**, *535*, 183–193.
[18] P. Wehman, P. C. J. Kamer, P. W. N. M. van Leeuwen, *Chem. Commun.* **1996**, 217–218.
[19] F. Ragaini, S. Cenini, *J. Mol. Catal. A* **1996**, *109*, 1–25, and references cited therein.
[20] R. Santi, A. M. Romano, P. Panella, G. Mestroni, *It. Pat. Appl.* MI96A 002071, **1996**.
[21] R. Santi, A. M. Romano, P. Panella, G. Mestroni, *It. Pat. Appl.* MI96A 002072, **1996**.
[22] R. Santi, A. M. Romano, R. Garrone, P. Panella, *It. Pat. Appl.* MI97A 000433, **1997**.
[23] R. Santi, A. M. Romano, P. Panella, C. Santini, *J. Mol. Catal. A* **1997**, *127*, 95–9.
[24] R. Santi, A. M. Romano, P. Panella, G. Mestroni, A. Sessanta o Santi, *J. Mol. Catal. A* **1999**, *144*, 41–45.
[25] P. Leconte, F. Metz, A. Mortreux, J. A. Osborn, F. Paul, F. Petit, A. Pillot, *J. Chem. Soc. Chem. Commun.* **1990**, 1616–1617.
[26] a) F. Paul, J. Fischer, P. Ochsenbein, J. A. Osborn, *Angew. Chem. Int. Ed. Engl.* **1993**, *32*, 1638–1640; b) F. Paul, J. Fischer, P. Ochsenbein, J. A. Osborn, *C. R. Chimie* **2002**, *5*, 267–287.
[27] A. Sessanta o Santi, B. Milani, G. Mestroni, E. Zangrando, L. Randaccio, *J. Organomet. Chem.* **1997**, *545–546*, 89–91.
[28] N. Masciocchi, F. Ragaini, S. Cenini, A. Sironi, *Organometallics* **1998**, *17*, 1052–1057.
[29] F. Paul, J. Fisher, P. Ochsenbein, J. A. Osborn, *Organometallics* **1998**, *17*, 2199–2206.
[30] E. Gallo, F. Ragaini, S. Cenini, F. Demartin, *J. Organomet. Chem.* **1999**, *586*, 190–195.
[31] A. Sessanta o Santi, B. Milani, E. Zangrando, G. Mestroni, *Eur. J. Inorg. Chem.* **2000**, 2351–2354.
[32] M. Gasperini, F. Ragaini, S. Cenini, E. Gallo, *J. Mol. Catal. A* **2003**, *204–205*, 107–114.
[33] F. Ragaini, E. Gallo, S. Cenini, *J. Organomet. Chem.* **2000**, *593–594,* 109–118.
[34] F. Ragaini, C. Cognolato, M. Gasperini, S. Cenini, *Angew. Chem. Int. Ed.* **2003**, *42*, 2886–2889; *Angew. Chem.* **2003**, *115*, 2992–2995.
[35] F. Ragaini, M. Gasperini, S. Cenini, *Adv. Synth. Catal.* **2004**, *346,* 63–71.
[36] J. S. Yadav, G. S. Reddy, M. M. Reddy, H. M. Meshram, *Tetrahedron Lett.* **1998**, *39*, 3259–3262.
[37] F. Ragaini, *Organometallics* **1996**, *15,* 3572–3578.
[38] a) H. des Abbayes, H. Alper, *J. Am. Chem. Soc.* **1977**, *99*, 98–101; b) H. Alper, D. Des Roches, H. des Abbayes, *Angew. Chem. Int. Ed. Engl.* **1977**, *16*, 41–41; c) H. Alper, H.-N. Paik, *Nouv. J. Chim.* **1978**, *2*, 245–247; d) H. Alper, L. C. Damude, *Organometallics* **1982**, *1*, 579–581; e) H. Alper, M. Gopal, *J. Chem. Soc. Chem. Commun.* **1980**, 821–821.
[39] H. Nishida, N. Takada, M. Yoshimura, T. Sonoda, H. Kobayashi, *Bull. Chem. Soc. Jpn.* **1984**, *57*, 2600–2604.
[40] H. Iwamoto, T. Sonoda, H. Kobayashi, *Tetrahedron Lett.* **1983**, *24*, 4703–4706.
[41] B. Milani, A. Anzilutti, L. Vicentini, A. Sessanta o Santi, E. Zangrando, S. Geremia, G. Mestroni, *Organometallics* **1997**, *16*, 5064–5075.
[42] M. Brookhart, B. Grant, A. F. Volpe Jr., *Organometallics* **1992**, *11*, 3920–3922.

[43] S. R. Bahr, P. Boudjouk, *J. Org. Chem.* **1992**, *57*, 5545–5547.
[44] 4-Chlorobenzoic acid was employed in ref.[18] instead of benzoic acid, but this is unlikely to make any large difference because the two promoters gave almost indistinguishable results when employed in the corresponding carbonylation of nitrobenzene.[15]
[45] F. Ragaini, M. Gasperini, S. Cenini, unpublished results.
[46] J. Bergman, P. Sand, *Tetrahedron* **1990**, *46*, 6085–6112.
[47] M. C. Carreño, J. M. Cuerva, M. Ribarorda, A. M. Echavarren, *Angew. Chem. Int. Ed.* **1999**, *38*, 1449–1452.
[48] a) F. Ragaini, A. Ghitti, S. Cenini, *Organometallics* **1999**, *18*, 4925–4933; b) F. Ragaini, S. Cenini, *J. Mol. Catal. A* **2000**, *161*, 31–38.
[49] M. Aresta, E. Quaranta, *Tetrahedron* **1991**, *47*, 9489–9502.
[50] W. V. Konze, B. L. Scott, G. J. Kubas, *Chem. Commun.* **1999**, 1807–1808.
[51] a) E. Drent, P. H. M. Budzelaar, *Chem. Rev.* **1996**, *96*, 63–81, and references cited therein; b) C. Querci, R. D'Alosio, R. Bortolo, M. Ricci, D. Bianchi, *J. Mol. Catal. A* **2001**, *176*, 95–100; c) A. Macchioni, A. Romani, C. Zuccaccia, G. Guglielmetti, C. Querci, *Organometallics* **2003**, *22*, 1526–1533.
[52] Y. Watanabe, Y. Tsuji, R. Takeuchi, *Bull. Chem. Soc. Jpn.* **1984**, *57*, 3011–3012.
[53] P. Tavs, *Chem. Ber.* **1970**, *103*, 2428–36.
[54] C. Yuan, H. Feng, *Synthesis* **1990**, 140–141.
[55] M. M. Kabachnik, M. D. Solntseva, V. V. Izmer, Z. S. Novikova, I. P. Beletskaya, *Russ. J. Org. Chem.* **1998**, *34*, 93–97; *Zh. Org. Khim.* **1998**, *34*, 106–111.