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Article

Synthesis and Catalytic Applications of Stable Palladium Dioxygen Complexes

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The synthesis and characterization of air-stable palladium dioxygen complexes $Pd(O_2)L_2$ of basic phosphines L = $P(1\text{-}Ad)_2{}^n Bu$, $P^tBu_2{}^nBu$ is described. Contrary to general belief, these dioxygen complexes are stable catalyst precursors for palladium-catalyzed coupling reactions. Specifically, palladium-catalyzed formylations and alkoxy carbonylations of aryl bromides proceed in high yield *in air* using commercial non-degassed solvents. It is shown that $Pd(O_2)L_2$ complexes are reduced back to the catalytically active palladium(0) species in the reductive atmosphere of CO or H_2 at the onset of the carbonylation reaction.

Palladium(0)-catalyzed transformations have become an essential tool in the contemporary arsenal of organic chemists due to their versatility, functional group tolerance, broad scope, and mild reaction conditions.[1,2] Generally, catalysts for these transformations are comprised of a palladium precursor and phosphine[3] or heterocyclic carbene ligands or, in the latter case, their salts.[4] Most of the known precatalysts are fairly air stable and can be conveniently weighted and handled in air as solids without taking special precautions. However, being dissolved in organic solvents during preparation of the reaction mixture, these precatalysts form highly air sensitive palladium(0) phosphine or carbene complexes. To avoid rapid catalyst decomposition, reaction mixtures for cross-coupling reactions should be prepared under rigorously air free conditions using either Schlenk or glovebox techniques. Obviously, the development of more convenient air-friendly protocols would simplify synthetic applications of palladium-catalyzed reactions, making them more straightforward and practical.

Herein, we describe a simple and efficient *air-tolerant* protocol for the palladium-catalyzed carbonylation of aryl bromides based on the application of novel stable palladium dioxygen complexes of di-1-adamantyl-*n*-butylphosphine and di-*tert*-butyl-*n*-butylphosphine. The method tolerates preparation of the reaction mixtures *in air* using *non-degassed solvents*, thus providing a considerable improvement in simplicity over previously reported carbonylation methods.

Results and Discussion

Recently, we reported improved protocols for Pd-catalyzed alkoxycarbonylations and formylations of aryl halides.[5,6] Crucial for the formation of the active catalyst was the use of bulky, unsymmetrical alkyl phosphines: either $P(1\text{-}Ad)_2{}^nBu$ or $P^tBu_2{}^nBu$ as ligand. On the basis of our studies, the formylation with synthesis gas (CO/H_2) in the presence of $Pd/P(1\text{-}Ad)_2{}^nBu$ is also performed in industry on a scale of tons, demonstrating the practical value of these transformations.[7]

Stoichiometric studies of the formylation of aryl bromides catalyzed by $Pd/P(1\text{-}Ad)_2{}^nBu$ demonstrated the corresponding hydrobromide palladium complex as the resting state of the catalyst, even in the presence of a large excess of base. Generation of the catalytically active Pd(0) species in small concentration upon reversible deprotonation of this complex was found to be responsible for the longevity of the catalyst.[8] Intrigued by these results, we continued to investigate the organometallic chemistry of palladium complexes bearing

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*To whom correspondence should be addressed. E-mail: matthias.beller@catalysis.de.

(1) (a) Li, J. J.; Limberakis, C.; Pflum., D. A. *Modern Organic Synthesis in the Laboratory. A Collection of Standard Experimental Procedures*; Oxford University Press: New York, 2007. (b) Miyaura, N., Ed. *Cross Coupling Reactions: A Practical Guide*; Springer-Verlag: Heidelberg, Germany, 2002; Topics in Current Chemistry Series, Vol. *219*.

(2) (a) Tsuji, J., *Palladium Reagents and Catalysts: New Perspectives for the 21st Century*, 2nd ed.; Wiley: Chichester, U.K., 2004. (b) Negishi, E.-i., Ed. *Handbook of Organopalladium Chemistry for Organic Synthesis*; Wiley: New York, 2002; Vols. 1 and 2.

(3) For general reviews see, for example, ref 2 and: (a) Fleckenstein, C. A.; Plenio, H. *Chem. Soc. Rev.* **2010**, *39*, 694. (b) Martin, R.; Buchwald, S. L. *Acc. Chem. Res.* **2008**, *41*, 1461. (c) Surry, D. S.; Buchwald, S. L. *Angew. Chem., Int. Ed.* **2008**, *47*, 6338. (d) Mauger, C. C.; Mignani, G. A. *Aldrichim. Acta* **2006**, *39*, 17. (e) Schlummer, B.; Scholz, U. *Adv. Synth. Catal.* **2004**, *346*, 1599.

(4) For general reviews, see: (a) Díez-González, S.; Marion, N.; Nolan, S. P. *Chem. Rev.* **2009**, *109*, 3612. (b) Díez-González, S.; Nolan, S. P. *Top. Organomet. Chem.* **2007**, *21*, 47. (c) Kantchev, E. A.; O'Brien, C. J.; Organ, M. G. *Angew. Chem., Int. Ed.* **2007**, *46*, 2768.

(5) (a) Neumann, H.; Brennführer, A.; Gross, P.; Riermeier, T.; Almena, J.; Beller, M. *Adv. Synth. Catal.* **2006**, *348*, 1255. (b) Brennführer, A.; Neumann, H.; Pews-Davtyan, A.; Beller, M. *Eur. J. Org. Chem.* **2009**, 38. (c) Neumann, H.; Brennführer, A.; Beller, M. *Adv. Synth. Catal.* **2008**, *350*, 2437.

(6) (a) Brennführer, A.; Neumann, H.; Klaus, S.; Riermeier, T.; Almena, J.; Beller, M. *Tetrahedron* **2007**, *65*, 6252. (b) Klaus, S.; Neumann, H.; Zapf, A.; Strübing, D.; Hübner, S.; Almena, J.; Riermeier, T.; Gross, P.; Sarich, M.; Krahnert, W.-R.; Rossen, K.; Beller, M. *Angew. Chem., Int. Ed.* **2006**, *45*, 154.

(7) (a) Zapf, A.; Beller, M. *Chem. Commun.* **2005**, 431. (b) Torborg, C.; Beller, M. *Adv. Synth. Catal.* **2009**, *351*, 3027.

(8) Sergeev, A. G.; Spannenberg, A.; Beller, M. *J. Am. Chem. Soc.* **2008**, *130*, 15549.

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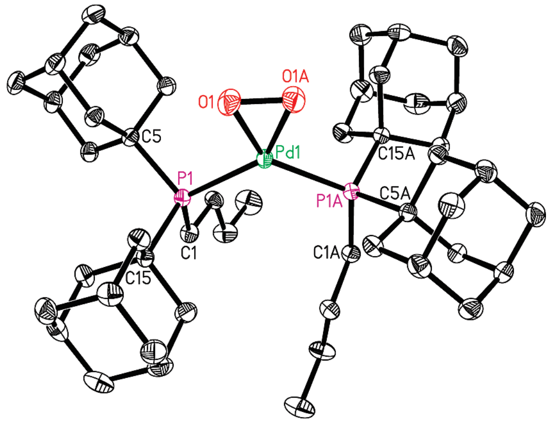
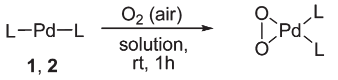


Figure 1. Molecular structure of **4**·(benzene). The thermal ellipsoids correspond to 30% probability. Hydrogen atoms are omitted for clarity.

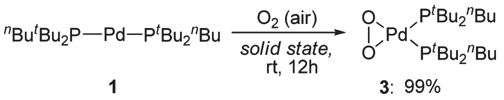
$P(1\text{-}Ad)_2{}^nBu$ and $P^tBu_2{}^nBu$ ligands. During these studies, we noticed that bis phosphine palladium(0) complexes of $P(1\text{-}Ad)_2{}^nBu$ and $P^tBu_2{}^nBu$ are easily oxidized in solution, leading to clean formation of the dioxygen complexes $Pd(O_2)L_2$. Thus, excposure of a heptane solution of $Pd(P^tBu_2{}^nBu)_2$ (**1**) and a benzene solution of $Pd\{P(1\text{-}Ad)_2{}^nBu\}_2$ (**2**)[9] to air at room temperature results in precipitation of the corresponding peroxo complexes **3** and **4** in 60% and 94% yields as green crystals (eq 1).



(1)

3: L = $P^tBu_2{}^nBu$ 60% (in heptane)
4: L = $P(1\text{-}Ad)_2{}^nBu$ 94% (in benzene)

Remarkably, the $P^tBu_2{}^nBu$-ligated palladium(0) complex **1** reacts with air even in the solid state at room temperature, yielding the corresponding peroxo complex **3** in quantitative yield as mint-colored crystals (eq 2). In contrast, a complex possessing isomeric tri-*tert*-butylphosphine, $Pd(P^tBu_3)_2$, does not react with oxygen in the solid state and does not produce any well-characterized peroxo complex in solution.[10,11]



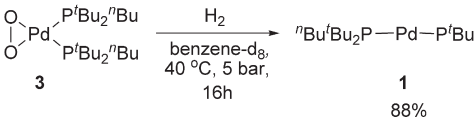
(2)

So far, only a few palladium(0) phosphine complexes produce stable peroxo complexes on exposure to air in solution.[10,12] Formation of the corresponding dioxygen palladium complexes in the solid state is even more rare. To the best of our knowledge, only one such example was described when crystalline $Pd(PPh^tBu_2)_2$ was reacted with air.[10,13,14]

Not surprisingly, palladium peroxo complexes **3** and **4** are both stable in air, differing only in thermal stability. Complex **4** can be stored at room temperature for at least 6 months, whereas **3** is stable only for several days at ambient temperature but can be kept for an unlimited time at subzero temperatures. Peroxo complex **4**, bearing di-1-adamantyl-*n*-butylphosphine, was characterized by X-ray data (see Figure 1). Emerald green crystals of **4**, suitable for a crystal structure analysis, were obtained by slow diffusion of air into a benzene solution of **2**.

Complex **4** contains the side-on-coordinated dioxygen, which is located in one plane with two coordinated phosphorus atoms and the metal center, as exemplified by the P1−Pd1−O1A−O1 dihedral angle of 0.5(3)°. The O−O bond in the coordinated dioxygen molecule of 1.395(4) Å is considerably longer than that in the free oxygen molecule (1.2074 Å)[15] and slightly shorter than the standard O−O single bond (e.g., 1.475 Å in hydrogen peroxide).[15] Coordination of dioxygen to palladium(0) complex **2** causes a considerable decrease in the P−Pd−P angle from 172.18(5)° in **2** to 114.71(4)° in **4** and leads to only a slight elongation of the Pd−P bonds from 2.286(2) to 2.3402(8) Å, respectively.

Interestingly, dioxygen in complexes **3** and **4** is coordinated irreversibly;[16] however, the peroxo complexes can be reduced back to Pd(0) complexes **1** and **2** by reaction with hydrogen under mild conditions. Thus, hydrogenation of complex **3** with hydrogen at 5 bar and 40 °C in benzene-d_8 led to the formation of palladium(0) complex **1**, as evidenced by the appearance of the singlet of **1** at δ 57.6 ppm in the ^{31}P NMR spectrum of the reaction mixture (eq 3). Due to poor solubility we did not perform the corresponding reaction with **4**. However, we obtained indirect proof that this complex converted to the palladium(0) species under a reductive atmosphere (CO/H_2) at elevated temperatures as well (vide infra).



(3)

Apart from hydrogen, complex **3** can also be reduced with CO (20 bar, 16 h) even in the solid state at room temperature to give the palladium(0) carbonyl cluster $Pd_n(CO)_m(P^tBu_2{}^nBu)_n$ (**5**) as the major palladium-containing product.[17]

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[9] When the reaction was carried out in toluene, the solution turned brown and no peroxo complex precipitated.

[10] (a) Matsumoto, M.; Yoshioka, K.; Nakatsu, K.; Yoshida, T.; Otsuka, S. *J. Am. Chem. Soc.* **1974**, *96*, 3322. (b) Yoshida, T.; Otsuka, S. *J. Am. Chem. Soc.* **1977**, *99*, 2134.

[11] Yamashita, M.; Goto, K.; Kawashima, T. *J. Am. Chem. Soc.* **2005**, *127*, 7294.

[12] (a) Wilke, G.; Schott, H.; Heimbach, P. *Angew. Chem., Int. Ed.* **1967**, *6*, 92. (b) Urata, H.; Suzuki, H.; Morooka, Y.; Ikawa, T. *J. Organomet. Chem.* **1989**, *364*, 235. (c) Amatore, C.; Aziz, S.; Jutand, A.; Meyer, G.; Cocolios, P. *New J. Chem.* **1995**, *19*, 1047. (d) Clegg, W.; Eastham, G. R.; Elsegood, M. R. J.; Heaton, B. T.; Iggo, J. A.; Tooze, R. P.; Whyman, R.; Zacchini, S. *Dalton Trans.* **2002**, 3300.

[13] Another example may include $Pd(PCy_3)_2$, but its reactivity to air in the solid state is controversial: in ref 10b, $Pd(PCy_3)_2$ is claimed to form the peroxo complex, whereas in ref 11, the same complex was found to be inert to air.

[14] For solid-state reactions of palladium(0) carbene complexes with air, see ref 11 and: Konnick, M. M.; Guzei, I. A.; Stahl, S. S. *J. Am. Chem. Soc.* **2004**, *126*, 10212.

[15] Lide, D. R.., Ed. *CRC Handbook of Chemistry and Physics*, 90th ed. (Internet Version 2010); CRC Press/Taylor and Francis: Boca Raton, FL, 2010.

[16] When a solution of **3** in benzene-d_6 was subjected to four freeze−pump−thaw cycles, no changes in ^1H and $^{31}P\{^1H\}$ NMR spectra were observed. Passing of argon via a benzene solution of **3** at 40 °C for 1 h caused formation of only traces of **1** and accumulation of a dark-colored product of decomposition. Heating of the less soluble complex **4** under vacuum at 60 °C for 1 h also did not lead to appreciable deoxygenation.

[17] According to a $^{31}P\{^1H\}$ NMR spectrum in benzene-d_6 three products formed: **5** free $P^tBu_2{}^nBu$, and an unidentified complex exhibiting three signals at 56.7 (s), 28.9 (br s), and 51.3 (br s) ppm in a ca. 2.8:1:0.6 ratio. Reaction conditions were not optimized.

The same complex **5** is obtained when **1** is carbonylated in the solid state.[18] Recently, we showed that such clusters $Pd_n(CO)_m(L)_n$ (L = $P^tBu_2{}^nBu$, $P(1\text{-}Ad)_2{}^nBu$) can be the resting state of the catalyst in the reductive carbonylation of aryl halides catalyzed by $Pd/P(1\text{-}Ad)_2{}^nBu$ or $P^tBu_2{}^nBu$.[8]

Clearly, the ability of the peroxo complexes **3** and **4** to generate catalytically active palladium(0) complexes under an atmosphere of hydrogen and carbon monoxide provides an opportunity to use **3** and **4** as convenient substitutes for their air-sensitive analogues **1** and **2**: e.g., as precatalysts in various coupling reactions. To demonstrate the viability of **3** and **4** as palladium precursors, we employed them initially in the reductive carbonylation of aryl halides with synthesis gas (CO/H_2) under the previously optimized reaction conditions (toluene, TMEDA as a base, 5 bar of CO/H_2, 100 °C). We were pleased to find that complexes **3** and **4** indeed catalyzed the formylation of a wide scope of aryl bromides at low catalyst loadings (0.25 mol %). As can be seen from Table 1, both electron-rich and electron-poor aryl halides are transformed into the corresponding benzaldehydes in moderate to excellent yields (42−99%). Functional groups such as CN and C(O)Me are well tolerated, and halogen substituents (Cl and F) remain intact toward hydrogenolysis as well (Table 1, entries 1, 2 and 4, 5). In general, reactions catalyzed by **4** proceed with better yields compared to those with complex **3**, as illustrated by entries 1, 3, 7, 8, and 10−12. Notably, the peroxo complex **4** was in most cases as efficient as the original precatalyst $Pd(OAc)_2/P(1\text{-}Ad)_2{}^nBu$.[6]

Having established for the first time the catalytic activity of palladium peroxo complexes in non-oxidative coupling reactions, we decided to exploit their tolerance to air and applied **4** to an *air-tolerant* formylation, including preparation of the reaction mixture *in air*. To further simplify the procedure, we used non-degassed and non-dried commercial toluene (Table 1). To our delight, under these conditions **4** was surprisingly efficient, even at catalyst loadings of 0.25 mol %! Thus, formylation of electron-deficient 4-halobromobenzenes and 4-bromobenzotrifluoride, as well as electron-rich 3- and 4-bromoanisoles and 4-bromo-*N,N*-dimethylaniline gave the corresponding benzaldehydes in good to excellent yields (80−97%) (Table 1, entries 1−3, 8, 10, and 11). However, in the case of some problematic substrates such as 3-bromothiophene and 2-bromoanisole, yields decreased by 20−25% as compared to the reactions under standard conditions (see Table 1, entries 5, 7, 9, and 12).

Next, we tested the original catalyst system comprised of $Pd(OAc)_2$ and air-stable crystalline $P(1\text{-}Ad)_2{}^nBu$ under the *air-tolerant* reaction conditions. It is known that the combination of $Pd(OAc)_2$ and phosphine ligands L in a ratio of 1:*N* can generate PdL_{N-1} complexes.[19,20] We assumed that mixing $Pd(OAc)_2$ and 3 equiv of $P(1\text{-}Ad)_2{}^nBu$ should similarly lead to the formation of $Pd\{P(1\text{-}Ad)_2{}^nBu\}_2$ (**2**) species. When the mixing is done in air, this species should be easily oxidized to give **4**, which is a suitable catalyst for the *air-friendly* formylation, as shown above.

Indeed, use of 0.25 mol % of $Pd(OAc)_2/3P(1\text{-}Ad)_2{}^nBu$ under *air-tolerant* conditions and subsequent application in the reductive carbonylation of aryl bromides with synthesis gas at 100 °C and 5 bar provided a convenient and easy-to-apply catalyst system. The catalyst showed high activity and proved to be as efficient—in some cases even more efficient—as in the experiments with complete exclusion of air (Table 1). All aryl bromides shown in Table 1 were formylated in good to excellent yields. Moreover, formylation of 4-bromobenzonitrile gave a higher yield (84%) under the air-friendly conditions, compared to the reaction employing the standard protocol (57%) (Table 1, entry 4). Under air-friendly conditions, $Pd(OAc)_2/P(1\text{-}Ad)_2{}^nBu$ gave also good results with problematic substrates such as 2-bromoanisole and 5-bromo-*m*-xylene (64% and 67% yields, respectively; Table 1, entries 9 and 12). In these cases the peroxo complex **4** performed less efficiently.[21] This difference in the catalytic behavior of the peroxo complex **4** and the in situ system $Pd(OAc)_2/3P(1\text{-}Ad)_2{}^nBu$ might be explained by the presence of acetate ions coming from palladium acetate, which is known to affect the catalytic performance of palladium(0) species.[20]

As we have shown above, **3** and **4** are reduced to palladium(0) species not only with hydrogen but also with carbon monoxide. This makes these complexes promising catalyst precursors for all kinds of palladium-catalyzed carbonylations.

Therefore, we tested **3** and **4** in the alkoxycarbonylation of aryl bromides under *air-tolerant* conditions using 0.5 mol % of the catalyst in neat *n*-butyl alcohol at 5 bar of CO in the presence of TMEDA as a base (Table 2). In line with our assumptions, peroxo complexes **3** and **4** both proved to be good catalysts under these conditions, affording the esters in 58−98% and 89−99% yields, respectively. The scope of the carbonylation encompassed both electron-rich and electron-deficient aryl bromides as well as heterocyclic 3-bromopyridine. As in the formylation reaction, the $P(1\text{-}Ad)_2{}^nBu$-ligated peroxo complex **4** was a more general catalyst than its $P^tBu_2{}^nBu$ analogue **3**. This is illustrated by the results of the carbonylation of challenging electron-rich substrates such as 4-bromoanisole and 4-bromo-*N*,*N*-dimethylaniline, where **4** gave the products in 89 and 99% yields, whereas the yields with **3** did not exceed 71% (Table 2, entries 2 and 4).[22] It is worth noting that under air-friendly conditions the peroxo complex **4** works as well as the original catalyst $Pd(OAc)_2/P(1\text{-}Ad)_2{}^nBu$ does under an inert atmosphere (Table 2). Additionally, the latter catalyst also gave excellent results in the presence of air (Table 2). To the best of our knowledge, no similar *air-tolerant* alkoxy or reductive carbonylations have been reported before.[23]

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(18) Carbonylation of solid **1** at 20 bar and room temperature for 16 h leads to the formation of **5** and $P^tBu_2{}^nBu$ as major products in a 1:1 ratio, according to the $^{31}P\{^1H\}$ NMR spectrum in benzene-d_6.

(19) See for example: (a) Amatore, C.; Jutand, A.; Khalil, F. *Arkivoc* **2006**, *IV*, 38. (b) Amatore, C.; Carré, E.; Jutand, A.; M'Barki, M. A. *Organometallics* **1995**, *14*, 1818. (c) Mandai, T.; Matsumoto, T.; Tsuji, J.; Saito, S. *Tetrahedron Lett.* **1993**, *34*, 2513. (d) Amatore, C.; Juntand, A.; M'Barki, M. A. *Organometallics* **1992**, *11*, 3009. (e) Ozawa, F.; Kubo, A.; Hayashi, T. *Chem. Lett.* **1992**, 2177.

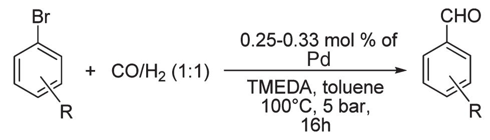
(20) For the role of $[Pd(OAc)L_2]^-$ intermediates in cross-coupling reactions, see for example: Amatore, C.; Jutand, A. *Acc. Chem. Res.* **2000**, *33*, 314.

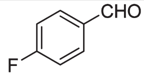
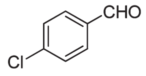
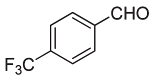
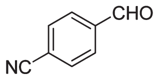
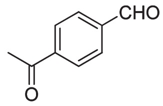
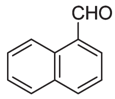
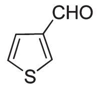
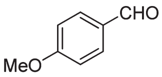
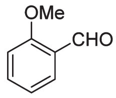
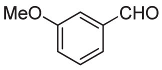
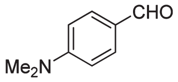
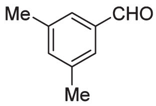
(21) To check if a different Pd:L ratio is responsible for the observed difference in reactivity of **4** (the ratio is 1:2) and $Pd(OAc)_2/3P(1\text{-}Ad)_2{}^nBu$ (the ratio is 1:3), we performed formylation of 1-bromonaphthalene, 4-bromoacetophenone and 4-bromobenzonitrile using a combination of 0.25 mol % of **4** and 0.25 mol % of added $P(1\text{-}Ad)_2{}^nBu$ ligand. Whereas for the first two aryl bromides the yields (89% for both substrates) were comparable to those with $Pd(OAc)_2/3P(1\text{-}Ad)_2{}^nBu$ (92 and 89% respectively), 4-bromobenzonitrile still gave the lower yield (59%) compared to $Pd(OAc)_2/3P(1\text{-}Ad)_2{}^nBu$ (84%).

(22) With regard to the limitation of this protocol, di-ortho-substituted 2-bromomesitylene gave only low yields of 15 and 30% in the reactions with **3** and **4**, respectively.

(23) (a) For a recent review on palladium-catalyzed carbonylations of aryl halides, see for example: Brennführer, A.; Neumann, H.; Beller, M. *Angew. Chem., Int. Ed.* **2009**, *48*, 4114 and references therein. (b) Note added in proof: recently Lei et al. reported Pd-catalyzed oxidative carbonylation of arylboronic acids via formation of $Pd(O_2)L_2$ intermediates: Liu, Q.; Li, G.; He, J.; Liu, J.; Lei, A. *Angew. Chem., Int. Ed.* **2010**, *49*, 3371.

Table 1. Reductive Carbonylation of Aryl Bromides Catalyzed by Peroxo Complexes 3 and 4 and Pd(OAc)$_2$/P(1-Ad)$_2{}^n$Bu under Inert and Air-Tolerant Conditions[a]

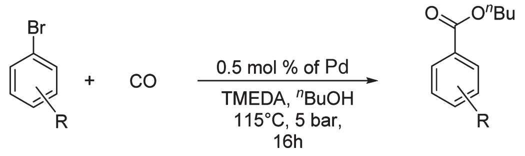


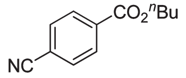
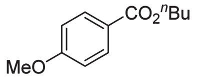
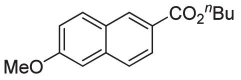
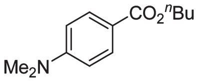
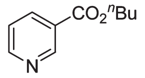
		Yield of ArCHO (conversion of ArBr), %[b]				
Entry	Product	*in argon*[c]			*in air*[d]	
		Complex **3**	Complex **4**	Pd(OAc)$_2$/ P(1-Ad)$_2{}^n$Bu[e]	Complex **4**	Pd(OAc)$_2$/ P(1-Ad)$_2{}^n$Bu
1		79 (81)	95 (98)	89 (98)	82 (85)	88 (99)
2		84 (100)	93 (100)	89 (100)	97 (100)	91 (100)
3		73 (100)	91 (100)	84 (100)	82 (100)	88 (100)
4		42 (58)	54 (74)	57 (77)[f]	44 (60)	84 (100)
5		77 (100)	80 (100)	88 (100)	55 (62)	89 (100)
6		82 (100)	85 (100)	86 (100)	77 (89)	92 (100)
7		75 (91)	87 (100)	82 (97)	63 (83)	85 (100)
8		69 (71)	83 (95)	96 (98)[f]	83 (87)	98 (98)
9		27 (34)	50(62)	63 (84)[f]	27 (35)	64 (71)
10		74 (81)	93 (99)	99 (99)	80 (88)	99 (99)
11		54 (58)	92 (99)	98 (99)	83 (90)	99 (100)
12		37 (42)	50 (62)	85 (85)	23 (25)	67 (84)

[a] Reaction conditions: 2 mmol of aryl bromide, 1.5 mmol of TMEDA, 0.4 mmol of hexadecane (internal standard for GC), 0.25 mol % of complex **3** or **4**, 2 mL of toluene, 5 bar of CO/H$_2$ (1:1), 100 °C, 16 h. [b] Determined by GC. [c] Reaction mixtures were prepared in argon. [d] Reaction mixtures were prepared in air using non-degassed commercial toluene. [e] See ref 6. [f] 0.33 mol % of palladium was used.

In summary, we have described an efficient *air-tolerant* protocol for palladium-catalyzed formylation and alkoxycarbonylation of aryl bromides at low catalyst loadings (0.25−0.5%). Our protocol features simple preparation of the reaction mixtures *in air* using commercial non-degassed solvents and simplifies the existing synthetic procedures. The success of this method is based on the remarkable ability of the palladium(0) complexes PdL$_2$ (L = P(1-Ad)$_2{}^n$Bu, P^{t}Bu$_2{}^n$Bu) to react with air, yielding the well-defined and stable peroxo complexes Pd(O$_2$)L$_2$, which are easily converted back to the

Table 2. Alkoxycarbonylation Catalyzed by Peroxo Complexes 3 and 4 and Pd(OAc)$_2$/P(1-Ad)$_2{}^n$Bu under Inert and Air-Tolerant Conditions[a]



Entry	Product	Yield (Conversion), %[b]			
		in air[c]			*in argon*[d]
		Complex **3**	Complex **4**	Pd(OAc)$_2$/ P(1-Ad)$_2{}^n$Bu	Pd(OAc)$_2$/ P(1-Ad)$_2{}^n$Bu
1		96 (100)	96 (100)	93 (100)	98 (98)
2		58 (66)	89 (97)	93 (100)	97 (97)
3		98 (100)	98 (100)	99 (100)	99 (99)
4		71 (72)	99 (100)	99 (100)	99 (99)
5		96 (100)	99 (100)	97 (100)	91 (91)

[a] Reaction conditions: 2 mmol of aryl bromide, 1.5 mmol of TMEDA, 0.4 mmol of hexadecane (internal standard for GC), 0.5 mol % of **3** or **4**, 2 mL of *n*-butyl alcohol, 5 bar of CO, 115 °C, 16 h. [b] Determined by GC. [c] The reaction mixture was prepared in air using non-degassed commercial *n*-butyl alcohol. [d] See ref 5a.

catalytically active palladium(0) complexes under carbonylation conditions.

Experimental Section

General Comments. Aryl halides and hexadecane were purchased from Aldrich and used as received. Benzadehydes and *n*-butyl benzoates (standards for GC analysis) were purchased from Aldrich or prepared according to literature procedures.[5a,6] Toluene and *n*-butyl alcohol were purchased from Merck. For the air-friendly carbonylations, solvents (toluene, *n*-butyl alcohol) were used straight from the bottle. For other reactions benzene and toluene were distilled over benzophenone ketyl; *n*-butyl alcohol, heptanes, and TMEDA were distilled from calcium hydride. Solvents were stored under argon in Aldrich Sure Stor flasks. Palladium acetate was purchased from Strem. Complexes **1** and **2** were prepared according to the literature procedures.[8] Di-1-adamantyl-*n*-butylphosphine (cata*CX*ium A) was donated by Evonik-Degussa, and *n*-butyl-di-*tert*-butylphosphine[24] was synthesized according to the literature procedure.

NMR spectra were recorded on Bruker ARX 300 and Bruker ARX 400 spectrometers. ^{13}C and ^{1}H NMR spectra were referenced to signals of deuterio solvents and residual protiated solvents, respectively. ^{31}P NMR chemical shifts are reported relative to 85% H$_3$PO$_4$. Gas chromatographic analysis was performed on a Agilent HP-5890 instrument with a FID detector and HP-5 capillary column (polydimethylsiloxane with 5% phenyl groups, 30 m, 0.32 mm i.d., 0.25 μm film using argon as carrier gas). Gas chromatographic−mass spectrometric analysis was carried out on an Agilent HP-5890 instrument with an Agilent HP-5973 mass selective detector (EI) and HP-5 capillary column (polydimethylsiloxane with 5% phenyl groups, 30 m, 0.25 mm i.d., 0.25 μm film thickness) using helium carrier gas.

Pd(O$_2$){P(1-Ad)$_2{}^n$Bu}$_2\cdot$C$_6$H$_6$ (4). Pd{P(1-Ad)$_2{}^n$Bu}$_2$ (41 mg, 4.98×10^{-2} mmol) was dissolved in 4 mL of benzene, and air was bubbled through the solution for 1 h. The resulting green precipitate was filtered and washed with benzene to give 44 mg (94%) of the product. Large crystals of **4** can be obtained by exposure of the benzene solution to air overnight. ^{1}H NMR (300 MHz, CDCl$_3$): δ, 7.36 (s, benzene), 2.16−2.34 (apparent bs, 24H), 1.93−2.09 (bs, 12H), 1.59−1.88 (m, 32H), 1.29−1.47 (m, 4H), 0.97 (t, J = 7 Hz, 6H). ^{13}C{^{1}H} NMR (75 Hz, CDCl$_3$): δ 128.3 (benzene), 40.9 (m, overlapping, *C*), 40.8 (overlapping, *C*H$_2$), 36.7 (*C*H$_2$), 29.3, 28.7 (t, J = 4 Hz, *C*H$_2$), 25.9 (t, J = 4.5 Hz, *C*H$_2$), 21.4 (t, J = 6 Hz, *C*H$_2$) 14.0 (*C*H$_3$). ^{31}P{^{1}H} NMR (121 MHz, C$_6$D$_6$): δ 60.3. Anal. Calcd for C$_{54}$H$_{86}$O$_2$P$_2$Pd: C, 69.47; H, 9.07. Found: C, 69.29; H, 9.55.

X-ray Crystal Structure Analysis of 4. Single crystals of **4** were grown by the slow diffusion of air into a solution of

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(24) Cooper, J. W.; Roberts, B. P. J. *J. Chem. Soc. Perkin Trans. 2* **1976**, 808.

complex **2** in benzene at room temperature. Data were collected on a STOE IPDS II diffractometer using graphite-monochromated Mo Kα radiation. The structure was solved by direct methods (SHELXS-97)[25] and refined by full-matrix least-squares techniques on F^2 (SHELXL-97).[25] XP (Bruker AXS) was used for the graphical representation. Crystal data: $C_{60}H_{90}O_2P_2Pd$, M_r = 1011.66, monoclinic, space group $C2/c$, a = 15.864(3) Å, b = 14.489(3) Å, c = 22.849(5) Å, β = 95.02(3)°, V = 5231.7(18) Å^3, Z = 4, ρ_{calcd} = 1.284 g cm^{-3}, μ = 0.458 mm^{-1}, T = 293 K, 33 863 reflections collected, 5150 independent reflections (R_{int} = 0.0688), of which 3768 were observed ($I > 2\sigma(I)$), final R indices ($I > 2\sigma(I)$) R1 = 0.0361 and wR2 = 0.0712, R indices (all data) R1 = 0.0572 and wR2 = 0.0742, 265 refined parameters.

$Pd(O_2)(P^tBu_2{}^nBu)_2$ (3). Synthesis in solution, **3** was prepared from **1** in 60% yield following the procedure for **4** using heptane as a solvent. Synthesis in the solid state: off-white crystals of **1** (51 mg, 0.1 mmol) were exposed to air overnight (12 h) at room temperature to give 54 mg of **3** as pale mint-colored crystals (99%). ^{1}H NMR (300 MHz, C_6D_6): δ 1.45−1.72 (m, 8H, 1.35 (apparent d, J = 13 Hz, 36H), 1.15−1.29 (apparent sextet, J = 7.5 Hz, 4H), 0.82 (t, J = 7.5 Hz, 6H). ^{13}C{^{1}H} NMR (75 Hz, C_6D_6): δ 35.8 (dd, J = 7 Hz, J = 5.5 Hz, C), 30.5 (t, J = 3 Hz, CH_3), 28.9 (CH_2), 25.9 (t, J = 5.5 Hz, CH_2), 24.1 (dd, J = 7 Hz, J = 5 Hz, CH_2), 13.9 (CH_3). ^{31}P{^{1}H} NMR (121 MHz, C_6D_6): δ 64.0. Anal. Calcd for $C_{24}H_{54}O_2P_2Pd$: C, 53.08; H, 10.02. Found: C, 52.86; H, 9.77.

Reduction of 3 with Hydrogen To Give 1. A 4 mL screw-cap vial was charged with **3** (27.6 mg, 5.08 × 10^{-3} mmol) and a magnetic stir bar and closed with a screw cap equipped with septum and inlet needle. The vial vas evacuated and filled with argon via the inlet needle, and 0.8 mL of degassed C_6D_6 was added via syringe. After brief stirring a green solution formed. The vial was placed in an alloy plate, which was transferred to a 300 mL autoclave from Parr Instruments (Model 4561) under an argon atmosphere. The autoclave was flushed with hydrogen and then pressurized to 5 bar at room temperature and heated at 40 °C for 16 h. After it was cooled to room temperature, the reaction vial was taken out from the autoclave and the dark brown solution was transferred into a NMR tube under argon. ^{1}H and ^{31}P{^{1}H} NMR spectra of the reaction mixture showed complete consumption of **3** and formation of **1** and a side product in an 8:1 ratio (the peak ratio in the ^{31}P{^{1}H} NMR spectrum; see the Supporting Information). ^{1}H NMR (300 MHz, C_6D_6; spectrum of **1**, selected signals: δ 1.84−2.02 (m, 4H), 1.57−1.74 (m, 4H), 1.43−1.46 (m, 4H), 1.36−1.43 (m, 4H), 1.33 (m, J = 6 Hz, 36H), 1.01 (t, J = 7.5 Hz, 6 H). ^{31}P{^{1}H} NMR (121 MHz, C_6D_6; spectrum of **1**): δ 57.6.[8]

General Procedure for the Air-Friendly Reductive Formylation of Aryl Bromides using 3 and 4. In air, a 4 mL screw-cap vial was charged with 5 × 10^{-3} mmol of **3** or **4**, 2 mmol of aryl bromide, 1.5 mmol of TMEDA, 0.4 mmol of hexadecane (internal standard), 2 mL of toluene, and a magnetic stir bar. The vial was closed with a screw cap equipped with a septum and inlet needle and placed in an alloy plate, which was transferred to a 300 mL autoclave from Parr Instruments (Model 4561) under an argon atmosphere. The autoclave was flushed with synthesis gas (a 1:1 CO/H_2 mixture) and then pressurized to 5 bar at room temperature and heated at 100 °C for 16 h. The conversion and product yield were determined by GC using an internal standard and authentic compounds.

General Procedure for Air-Friendly Reductive Formylation of Aryl Bromides using $Pd(OAc)_2/P(1\text{-}Ad)_2{}^nBu$. The procedure is similar to that described above, except 5 × 10^{-3} mmol of $Pd(OAc)_2$ and 15 × 10^{-3} mmol of $P(1\text{-}Ad)_2{}^nBu$ were used instead of **4**.

General Procedure for Air-Friendly Alkoxycarbonylation of Aryl Bromides using 3 and 4. In air, a 4 mL screw-cap vial was charged with 1 × 10^{-2} mmol of **3** or **4**, 2 mmol of aryl bromide, 1.5 mmol of TMEDA, 0.4 mmol of hexadecane (internal standard), 2 mL of *n*-butyl alcohol, and a magnetic stir bar. The vial was closed with a screw cap equipped with a septum and inlet needle and placed in an alloy plate, which was transferred to a 300 mL autoclave from Parr Instruments (Model 4561) under an argon atmosphere. The autoclave was flushed with carbon monoxide and then pressurized to 5 bar at ambient temperature and heated at 115 °C for 16 h. The conversion and product yield were determined by GC using an internal standard and authentic compounds.

General Procedure for Air-Friendly Alkoxycarbonylation of Aryl Bromides using $Pd(OAc)_2/P(1\text{-}Ad)_2{}^nBu$. The procedure is similar to that described above, except 1 × 10^{-2} mmol of $Pd(OAc)_2$ and 3 × 10^{-2} mmol of $P(1\text{-}Ad)_2{}^nBu$ were used instead of **4**.

Acknowledgment. We thank Dipl. Ing. A. Koch, Mrs. S. Leiminger, and Ms. A. Kammer (all LIKAT) for their excellent analytical and technical support.

Supporting Information Available: Crystallographic data for **4** (CIF) NMR spectra of **3** and **4**. This material is available free of charge via the Internet at http://pubs.acs.org.

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[25] Sheldrick, G. M. *Acta Crystallogr.* **2008**, *A64*, 112–122.