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# Efficient Aerobic Wacker Oxidation of Styrenes Using Palladium Bis(isonitrile) Catalysts

**Anu Naik,[a] Liu Meina,[a] Manfred Zabel,[b] and Oliver Reiser*[a]**

**Abstract:** The palladium-catalyzed aerobic oxidation of alkenes and especially styrenes (Wacker oxidation) by using chiral pseudo $C_2$-symmetrical bis(isonitrile) ligands in the absence of further cocatalysts gives rise to methyl ketones in a highly chemoselective manner. The palladium bis(isonitrile) catalyst was characterized by NMR spectroscopy and X-ray structure analysis, revealing a dissymmetric coordination of palladium by the two isonitrile moieties.

**Keywords:** isonitriles · methyl ketones · palladium · styrenes · Wacker oxidation

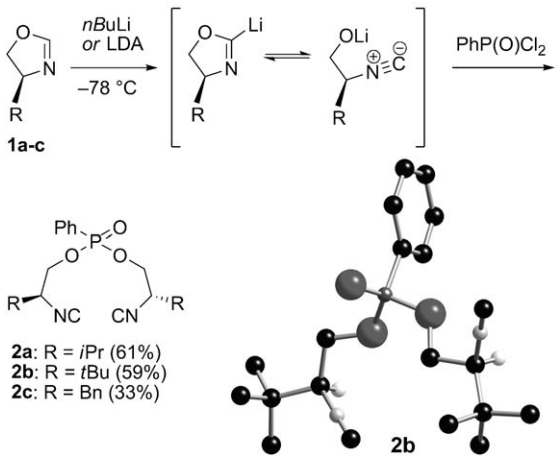
## Introduction

The palladium(II)-catalyzed oxidation of alkenes to methyl ketones, known as the Wacker oxidation, is one of the most important catalytic applications in industry.[1] The original protocol calls for stoichiometric amounts of copper(II) chloride as cocatalyst, which has been recognized as a considerable limitation for the overall process. Sustainable alternatives have been developed, notably the application of *tert*-butylhydroperoxide for the oxidation of styrenes[2] or molecular oxygen for the oxidation of alkyl-substituted terminal alkenes.[3] The coordination of palladium with strong σ-donor ligands, that is, *N*-heterocyclic carbenes or sparteine proved to be crucial for these successful developments.

Isonitriles are recognized as valuable synthons in organic synthesis,[4] but have been less frequently applied as ligands for metal catalysts.[5] Owing to their electronic properties, being also strong σ-donor ligands like *N*-heterocyclic carbenes, we thought that palladium isonitrile complexes might be also candidates for aerobic Wacker oxidations. Moreover, we envisioned that bidentate bis(isonitrile) ligands, being to the best of our knowledge unexplored in catalysis, might lead to chelated metal complexes with especially large bite angles, a feature that has proved to be especially beneficial for activity and selectivity in palladium-catalyzed cross-coupling reactions.[6]

## Results and Discussion

Oxazoles can be converted into isonitriles upon metalation followed by trapping of the resulting anion with hard electrophiles such as acetyl chloride or trimethylsilyl chloride.[7] Following our interest in using oxazolines as building blocks for multidentate ligand synthesis,[8] we applied this strategy to chiral oxazolines **1** and phenylphosphonic dichloride, from which bis(isonitriles) **2** were obtained (Scheme 1). The




Scheme 1. Synthesis of BINC ligands **2**, and X-ray structure of complex **2b**.

[a] A. Naik, L. Meina, Prof. Dr. O. Reiser
Institut für Organische Chemie, Universität Regensburg
Universitätsstrasse 31, 93053 Regensburg (Germany)
Fax: (+49) 941-9434121
E-mail: Oliver.Reiser@chemie.uni-regensburg.de

[b] Dr. M. Zabel
Institut für Anorganische Chemie, Universität Regensburg
Universitätsstrasse 31, 93053 Regensburg (Germany)

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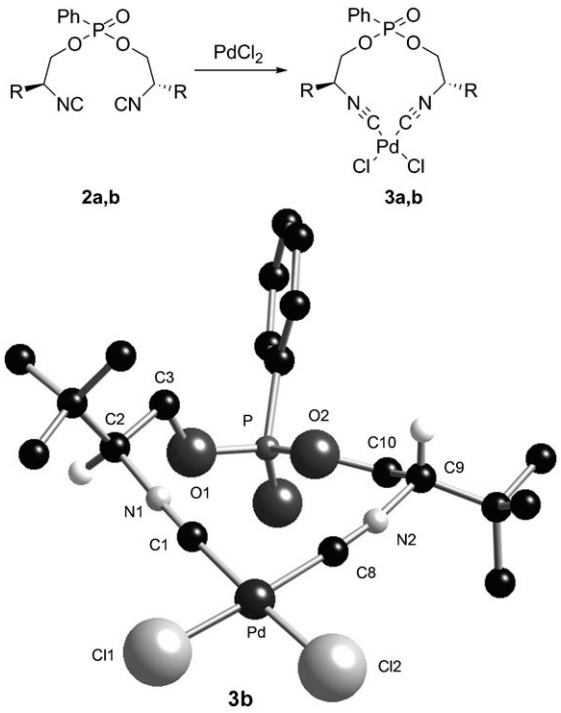
best results for the valine- and *tert*-leucine-derived ligands **2a,b** were observed when lithium diisopropylamide (LDA) was used as base, while **2c** could only be obtained in lower yield by applying *n*BuLi for deprotonating **1c.**

No erosion of stereochemistry was observed in the course of the reaction, which gave rise to the new BINC ligands **2** as odorless compounds in enantiomerically pure form. The structure of **2b** was unambiguously established by X-ray analysis,[9] which revealed a dissymmetric arrangement of the two diastereotopic isonitrile arms in the solid state that are also clearly distinguishable, in both the $^{1}H$ and $^{13}C$ NMR spectra.

The BINC ligands **2** readily form metal complexes with a broad variety of transition metals. Relevant for this study, complexation of **2a**,**b** with $[PdCl_2(PhCN)_2]$ gave rise to the $Pd^{II}$ complexes **3a**,**b**, which were characterized by NMR spectroscopy as well as by an X-ray structure analysis of **3b** (Scheme 2, Table 1). The latter revealed that **2b** indeed acts as a bidentate ligand forming with palladium a 12-membered chelate ring. Nevertheless, the bite angle between the isonitrile arms at the palladium center is with 88°, quite normal for a square-planar $d^8$ complex, which is realized by a dissymmetric arrangement of the two isonitrile moieties around the metal center. This geometry is also reflected in solution, as can be seen from the $^{1}H$ NMR spectrum of **3b**, which displays one set of signals for each isonitrile arm (see the Supporting Information).




Scheme 2. Synthesis of **3a,b** and X-ray structure of the $Pd^{II}$ complex **3b**.

Table 1. Selected bond lengths [Å] and angles [°] of **3b**.[a]

| Bond lengths [Å] | | Bond angles [°] | |
|---|---|---|---|
| Pd–Cl1 | 2.296 | C1-Pd-C8 | 88.2 |
| Pd–Cl2 | 2.299 | Cl1-Pd-Cl2 | 93.7 |
| Pd–C1 | 1.943 | Pd-C1-N1 | 177.2 |
| Pd–C8 | 1.935 | Pd-C8-N2 | 174.4 |
| C1–N1 | 1.128 | C1-N1-C2 | 177.6 |
| C8–N2 | 1.136 | C8-N2-C9 | 171.8 |
| N1–C2 | 1.457 | C1-N1-C2-C3 | 62.5 |
| N2–C9 | 1.453 | C8-N2-C9-C10 | 43.6 |

[a] For atom numbering see Scheme 2.

Recently, Sigman and Cornell discovered the direct palladium-catalyzed Wacker oxidation of terminal alkenes without the need for employing copper cocatalysts.[3] Palladium [(−)-sparteine] dichloride proved to be efficient for the conversion of aliphatic alkenes to methyl ketones using molecular oxygen as the terminal oxidant. This palladium complex proved also to be applicable for the oxidation of 4-methylstyrene to the corresponding methyl ketone when an excess of *tert*-butylhydroperoxide (TBHP, 5.5 equiv) was employed. Alternatively, a palladium(II)–NHC complex in the presence of catalytic amounts of AgOTf as cocatalyst using again TBHP as the terminal oxidant was reported by the same authors to be efficient for the generally more challenging oxidation of styrenes, a process that is often hampered by competing C=C-bond cleavage.[2] Moreover, Kaneda and co-workers disclosed that $[Pd(CH_3CN)_2Cl_2]$ is a Wacker catalyst that can be used under 6 atm oxygen pressure.[10]

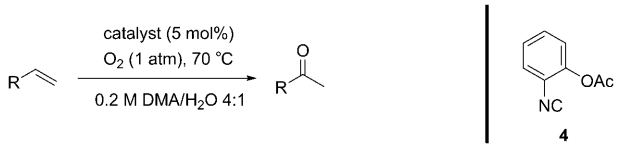
Inspired by these results, we tested **3a**,**b** in the oxidation of terminal alkenes in the absence of any further cocatalysts using molecular oxygen at ambient pressure. An initial screening revealed that both complexes give very similar yields and selectivities in Wacker oxidations (Table 3, entries 5 and 10). Therefore, we subsequently evaluated **3b**, which can be isolated in high puritiy by recrystallization and stored without signs of decomposition. Compound **3b** effectively catalyzed the oxidation of aliphatic alkenes (Table 2) by using dimethylacetamide (DMA)/water[3] as the solvent system. Careful GC analyses revealed that no isomerization or C=C-bond cleavage had occurred, and that the corresponding methyl ketones were generated in high yields and excellent purity. Terminal alkenes possessing oxygenated functional groups were found to be suitable substrates as well, and, notably, hydroxyl groups were not oxidized under the reaction conditions.

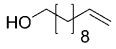
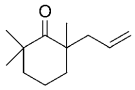
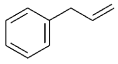
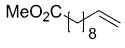
As a control experiment, we performed the oxidation of 1-octene also with the palladium(II) complex of the monodentate isonitrile ligand **4**,[7e] which also proceeded well but

**Abstract in German:** *Die aerobe Palladium-katalysierte Oxidation von Alkenen zu Methylketonen (Wacker Oxidation), insbesondere von Styrolen, gelingt mit chiralen Pseudo-$C_2$-symmetrischen Bisisonitrilliganden ohne weitere Cokatalysatoren mit hoher Chemoselektivität. Strukturelle Untersuchungen der Katalysatoren mittels NMR und Röntgenstrukturanalyse ergab, dass sowohl in Lösung wie auch im Festkörper Palladium unsymmetrisch durch die zwei Isonitrileinheiten koordiniert wird.*

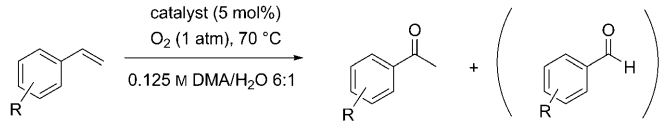
Table 2. Wacker oxidation of aliphatic alkenes.




| Entry | Catalyst | Substrate | Reaction time [h] | Conversion [%][a] |
|---|---|---|---|---|
| 1 | **3b** | 1-octene | 24 | 98 (75) |
| 2 | $[PdCl_2\cdot(\mathbf{4})_2]$[c] | 1-octene | 24 | 98[d] |
| 3 | **3b** |  | 48 | 97[e] (77) |
| 4 | **3b** |  | 48 | 92 (71) |
| 5 | **3b** |  | 48 | 75 |
| 6 | **3b** |  | 48 | 84 |
| 7 | **3b** |  | 48 | 98 |

[a] Determined by GC using decane as the internal standard; isolated yields in parentheses. [b] 5 mol% $PdCl_2$, 10 mol% **4**. [c] 3% isomerized alkene oxidation products. [d] Reaction conditions: 0.125 M concentration of substrate, 6:1 DMA/$H_2O$.

Table 3. Wacker oxidation of aromatic alkenes.




| Entry | Catalyst | R | Reaction time [h] | Conversion [%][a] | Ketone/ aldehyde |
|---|---|---|---|---|---|
| 1 | $PdCl_2$ | 4-Me | 70 | >99 | 4 |
| 2 | $[PdCl_2\cdot(\mathbf{4})_2]$ | 4-Me | 70 | >99 | 6 |
| 3[b] | **3b** | 4-Me | 70 | 91 | 18 |
| 4[c] | **3b** | 4-Me | 40 | >99 | 21 |
| 5 | **3b** | 4-Me | 40 | >99 | 26 |
| 6[d] | **3b** | 4-Me | 70 | 81 | 14 |
| 7[e] | **3b** | 4-Me | 40 | 98 | 14 |
| 8[f] | **3b** | 4-Me | 40 | 96 | 6 |
| 9[g] | **3b** | 4-Me | 40 | 90 | 8 |
| 10 | **3a** | 4-Me | 40 | 98 | 23 |
| 11 | **3b** | H | 70 | 84 | 17 |
| 12 | **3b** | 2-vinyl-naphthalene | 70 | 88 | 11 |
| 13 | **3b** | 3-Cl | 96 | 72 | 7 |
| 14 | **3b** | 4-Cl | 96 | 98 | 7 |
| 15 | **3b** | 4-Br | 96 | 50 | 9 |
| 16 | **3b** | 4-OMe | 48 | >99(75) | 21 |

[a] Determined by GC using decane as internal standard; isolated yields in parentheses. [b] DMA/water 2:1. [c] DMA/water 4:1. [d] Reaction temperature 100°C. [e] 2.5 mol% **3b**. [f] 1 mol% **3b**. [g] 1 mol% **3b** + 2 mol% **2b**.

gave around 3% of oxidation products stemming from alkene isomerizations.

Turning to the more challenging styrenes because of their propensity for C=C-bond cleavage under oxidative conditions, we were delighted to find that also for these substrates **3b** is effective at ambient oxygen pressure in the absence of any further cocatalyst (Table 3). A reaction temperature of 70°C and a DMA/water mixture of 6:1 was found to give the highest ratios between methyl ketones and aldehydes (Table 3, entry 5). As shown for the oxidation of 4-methylstyrene, the bidentate bis(isontrile) ligand **2b** is clearly superior to the monodentate isonitrile ligand **4** (Table 3, entry 2) or palladium chloride alone (Table 3, entry 1). Electron-rich styrenes showed higher reactivity, but also better selectivity towards methyl ketone formation than electron-poor derivatives. Nevertheless, good yields and selectivities could be obtained also for the latter (Table 3, entries 8–10).

Attempts to lower the catalyst concentration were not successful: While the conversion of substrates still proceeds well even at 1 mol% **3b**, substantially higher amounts of aldehydes are observed due to carbon–carbon bond cleavage (Table 1, entries 7–9), suggesting that the palladium isonitrile complexes are not stable under the reaction conditions and that background reactions involving palladium(0) alone occur over time. Control experiments showed that **2b** is stable in a 6:1 DMA/water mixture even at 100°C for elongated times. However, **2b** showed appreciable decomposition in a 6:1 DMA/water mixture at a reaction temperature of 70°C when palladium(II)chloride is present. In addition, when **2b** is employed in excess with respect to palladium, complete decomposition of **2b** is observed over time. Judged by the disappearance of the isonitrile band in the IR spectrum, we speculate that palladium(II) is capable of activating **2b** towards the attack of nucleophiles such as water present in the reaction, however, we did not observe the corresponding formamides that would result from addition of water to **2b.**

## Conclusions

In conclusion, the novel palladium–bis(isonitrile) complex **3b** was synthesized and fully characterized and was used for the aerobic oxidation of terminal aliphatic and aromatic alkenes in good yields and selectivities. No cocatalysts had to be employed, which is, to the best of our knowledge, unprecedented for styrenes when molecular oxygen is used at ambient pressure as the terminal oxidant.[11] Further exploration of the BINC ligands introduced here in other metal-catalyzed reactions is currently ongoing in our laboratories.

## Experimental Section

All reagents, unless otherwise specified were purchased from commercial sources and used without further purification. THF, diethyl ether, and toluene were distilled over sodium/benzophenone. DMA was dried over vacuum activated 4 Å molecular sieves. GC conversions for the reactions were determined relative to decane as an internal standard.

**Synthesis of BINC ligands**

**2a**: *n*-Butyllithium (15% in hexane, 0.5 mL, 1.15 mmol) was added to a solution of diisopropylamine (0.2 mL, 1.42 mmol) in THF (4 mL) under

nitrogen atmosphere at 0°C. After the mixture had been stirred for 15 min it was cooled down to −78°C and isopropyl-2-oxazoline (**1a**, 100 mg, 0.885 mmol) in THF (4 mL) was added. The mixture was stirred for 30 min, and then phenylphosphonic dichloride (0.07 mL, 0.53 mmol) was added followed by immediate removal of the cooling bath. Subsequently, the mixture was allowed to stir at room temperature for 2 h. Aqueous $NH_4Cl$ solution was added followed by workup of the mixture with ethyl acetate and brine. The organic layer was dried over $Na_2SO_4$ and concentrated under vacuum, and the residue was purified on silica (hexanes/ethyl acetate 2:3, $R_f=0.52$). Yield: 113 mg, 61%, yellowish viscous liquid. $[\alpha]^{20}_D=+36$ ( $c=1.0$, $CHCl_3$); IR (neat): $\tilde{\nu}=2969$, 2141, 1595, 1475, 1442, 1253 $cm^{-1}$; $^1H$ NMR ($CDCl_3$, 300 MHz): $\delta=7.80$–7.90 (m, 2H), 7.58–7.66 ( m, 1H), 7.48–7.55 (m, 2H), 4.03–4.28 (m, 4H), 3.63–3.76 (m, 2H), 1.88–2.03 (m, 2H), 1.03 (d, 6H), 1.01 ppm (d, 6H); $^{13}C$ NMR ($CDCl_3$, 75.5 MHz): $\delta=158.3$ (CN), 133.37 (d, $J=2.8$ Hz), 131.88 (d, $J=10.5$ Hz), 128.85(d, $J=15.4$ Hz), 126.05 (d, $J=190.9$ Hz), 65.49, 60.80, 28.83, 28.78, 19.40, 19.34, 17.09, 16.97 ppm; $^{31}P$ NMR ($CDCl_3$, 121.5 MHz): $\delta=20.78$ ppm (s); MS (EI-MS): $m/z$: $[M+H^+]$ 349, $[MNH_4^+]$ 366; HRMS: calcd for $C_{18}H_{25}O_3N_2P$ $[M^+]$: 348.160, found: 348.1603.

**2b**: *n*-Butyllithium (15% in hexane, 0.22 mL, 0.512 mmol) was added to a solution of diisopropylamine (0.09 mL, 0.630 mmol) in THF (2 mL) under nitrogen atmosphere at 0°C. After the mixture had been stirred for 15 min it was cooled down to −78°C and *tert*-butyl-2-oxazoline (**1b**, 50 mg, 0.394 mmol) in THF (2 mL) was added. The mixture was stirred for 30 min, and then phenylphosphonic dichloride (0.03 mL, 0.236 mmol) was added followed by immediate removal of the cooling bath. Subsequently, the mixture was allowed to stir at room temperature for 2 h. Aqueous $NH_4Cl$ solution was added followed by workup of the mixture with ethyl acetate and brine. The organic layer was dried over $Na_2SO_4$ and concentrated under vacuum, and the residue was purified on silica. (hexanes/ethyl acetate 2:3, $R_f=0.56$). Yield: 52 mg, 59%, white solid. $[\alpha]^{20}_D=+83$ ($c=1.0$, $CHCl_3$); IR (KBr): $\tilde{\nu}=2964$, 2140, 1594, 1475, 1442, 1394, 1370, 1346, 1246, 926 $cm^{-1}$; $^1H$ NMR ($CDCl_3$, 300 MHz): $\delta=7.87$ (dd, 2H, $J=7$ Hz, 13.8 Hz), 7.61(t, 1H, $J=7.5$ Hz), 7.45–7.54 (m, 2H), 4.28- 4.36 (m, 1H), 4.16–4.27 (m, 2H), 4.01 (q, 1H, $J=9.2$ Hz), 3.68 (dd, 1H, $J=3.1$, 9.1 Hz), 3.54 (dd, 1H, $J=3.8$, 8.9 Hz), 1.03 ppm (s, 18H); $^{13}C$ NMR ($CDCl_3$, 75.5 MHz): $\delta=158.37$ (NC), 133.45 (d, $C_{Ar-p}$, $J=3.05$ Hz)), 132.06 (d, $C_{Ar-o}$, $J=10.3$ Hz), 128.96 (d, $J=15.5$ Hz), 126.4 (d, $J=191$ Hz), 65.07, 64.77, 33.56 , 33.50, 26.37 ppm; $^{31}P$ NMR ($CDCl_3$, 121.5 MHz): $\delta=20.96$ ppm (s); MS (EI-MS), $m/z$: $[M+H^+]$ 377, $[MNH_4^+]$ 394. HRMS: calcd for $C_{20}H_{29}O_3N_2P$ $[M^+]$: 376.190, found: 376.191.

**2c**: *n*-Butyllithium (15% in hexane, 1.7 mL, 4.04 mmol) was added to a solution of benzyl-2-oxazoline (**1c**, 500 mg, 3.11 mmol) in THF (40 mL) under nitrogen atmosphere at −78°C. After the mixture had been stirred for 30 min, and then phenylphosphonic dichloride (0.3 mL, 1.9 mmol) was added followed by immediate removal of the cooling bath. Subsequently, the solution was allowed to stir at room temperature for 2 h. Aqueous $NH_4Cl$ solution was added, followed by workup of the mixture with ethyl acetate. The organic layer was dried over $Na_2SO_4$ and concentrated under vacuum, and the residue was purified on silica. (hexanes: ethyl acetate = 2:3, $R_f=0.47$). Yield: 276 mg, 33%, yellowish viscous liquid. $[\alpha]^{20}_D=+3.4$ ( $c=1.5$, $CHCl_3$); IR (KBr): $\tilde{\nu}=2140$, 1593, 1495, 1253, 961, 746 $cm^{-1}$; $^1H$ NMR ($CDCl_3$, 300 MHz): $\delta=7.83$–7.91 (m, 2H), 7.61–7.66 (m, 1H), 7.49–7.56 (m, 2H), 7.17–7.36 (m, 10H), 4.11–4.28 (m, 3H), 3.97–4.06 (m, 3H), 2.97 ppm (t, 4H); $^{13}C$ NMR ($CDCl_3$, 75.5 MHz): $\delta=159.01$ (NC), 134.82, 133.60 (d, $J=3.05$ Hz), 132.06 (d, $J=10$ Hz), 129.38, 129.04 (d, $J=15$ Hz), 129.02, 127.76, 126.06 (d, $J=191$ Hz), 65.80, 56.09, 37.64 ppm; $^{31}P$ NMR ($CDCl_3$, 121.5 MHz): $\delta=20.77$ ppm (s); MS (ES-MS): $m/z$: $[M+H^+]$ 455, $[MH^++H_2O]$ 463; HRMS: calcd for $C_{26}H_{26}O_3N_2P$ $[MH^+]$: 445.168, found: 445.167.

**[$PdCl_2$(*t*Bu-BINC)] (3b)**: A mixture of diisonitrile ligand (**2b**, 50 mg, 0.133 mmol) and $[PdCl_2(PhCN)_2]$ (50 mg, 0.131 mmol) in dichloromethane (2 mL) was stirred at room temperature for 16 h. The mixture was filtered through a small pad of celite and washed with dichloromethane. The filtrate wasconcentrated to a volume of approximately 0.5 mL. The crude product was precipitated by addition of hexane (1 mL) and the solvent was decanted after stirring for 10 min. This procedure was repeated three times. The resulting solid was washed with diethyl ether (3×1 mL) to give **3a** (67 mg, 91% yield) as a white solid. Crystals suitable for X-ray-crystallography were obtained by recrystallization of **3** from benzene. IR (neat): $\tilde{\nu}=2237$ (CN); 1250 (P=O); 343, 321 (Pd-Cl) $cm^{-1}$; $^1H$ NMR ($CDCl_3$, 300 MHz): $\delta=1.05$ (s, 9H), 1.12 (s, 9H), 3.93 (dd, 1H, $J=10.3$ Hz, 3.19 Hz), 3.98 (ddd, 1H, $J=10.5$ Hz, 11.08 Hz, 7.6 Hz), 4.16 (dd, 1H, $J=7.6$ Hz, 4.2 Hz), 4.18 (ddd, 1H, $J=3.6$ Hz, 10.9 Hz, 3.2 Hz), 4.29 (ddd, 1H, $J=7.6$ Hz, 11.08 Hz, 4.2 Hz), 4.49 (ddd, 1H, $J=8.4$ Hz, 10.9 Hz, 10.3 Hz), 7.55–7.64 (m, 2H), 7.65–7.74 (m, 1H), 7.77–7.88 ppm (m, 2H); $^{13}C$ NMR ($CDCl_3$, 150 MHz): $\delta=26.29$, 33.95, 62.94, 64.20, 67.95, 68.72, 119.67 (NC), 120.94 (NC), 125.23 (d, $J=187$ Hz), 129.26, 131.81, 133.90 ppm; $^{31}P$ NMR ($CDCl_3$, 121.5 MHz): $\delta=21.05$ ppm (s); elemental analysis calcd (%) for $C_{20}H_{29}Cl_2N_2O_3PPd$: C 43.38, H 5.28, N 5.06; found: C 42.88, H 5.50, N 4.83.

**Representative procedure for the Wacker oxidation of alkenes**: In a flame-dried 10 mL Schlenck tube equipped with a sidearm and stir bar, a mixture of [$PdCl_2$(*t*Bu-BINC)] (**3**; 14 mg, 5 mol%) and a 6:1 (v/v) solution of DMA:$H_2O$ (4 mL) were heated at 70°C for 10 min to assure complete solubility of the catalyst. The tube was allowed to cool to room temperature and connected with a condenser and a one-way joint with a balloon of $O_2$. The tube was evacuated (50 mbar) and refilled with $O_2$ three times. The reaction mixture was stirred vigorously for 10 min after which the alkene (0.5 mmol) was added. The mixture was then heated at 70°C for the indicated reaction time. After cooling to room temperature, the reaction mixture was analyzed by GC using decane as the internal standard.

For product isolation diethyl ether was added to the reaction mixture followed by extraction twice with 1N HCl. The aqueous layers were combined and extracted three times with diethyl ether. The organic layers were combined and washed with brine, dried over $Na_2SO_4$, and concentrated. The residue was purified by flash silica chromatography.

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[1] Leading reviews: a) J. Smidt, W. Hafner, R. Jira, R. Sieber, J. Sedlmeier, A. Sabel, *Angew. Chem.* **1962**, *74*, 93–102; *Angew. Chem. Int. Ed. Engl.* **1962**, *1*, 80–88; b) L. Hintermann in *Handbook of C-H Transformations* (Ed.: G. Dyker), Wiley-VCH, Weinheim, **2005**, pp. 287–302; c) J. M. Takacs, X. T. Jiang, *Curr. Org. Chem.* **2003**, *7*, 369–396; d) J. Muzart, *Tetrahedron* **2007**, *63*, 7505–7521.

[2] M. S. Sigman, C. N. Cornell, *J. Am. Chem. Soc.* **2005**, *127*, 2796–2797.

[3] M. S. Sigman, C. N. Cornell, *Org. Lett.* **2006**, *8*, 4117–4120.

[4] Leading reviews: a) Y. Ito, *Pure Appl. Chem.* **1990**, *62*, 583; b) J. Zhu, *Eur. J. Org. Chem.* **2003**, 1133; c) A. Dömling, *Chem. Rev.* **2006**, *106*, 17–89.

[5] Representative examples: a) M. Murakami, M. Suginome, K. Fujimoto, H. Nakamura, P. G. Anderson, Y. Ito, *J. Am. Chem. Soc.* **1991**, *113*, 3987–3988; b) T. A. Nile, K. P. Adams, J. A. Joyce, A. I. Patel, C. D. Reid, J. M. Walters, *Mol. Catal.* **1985**, *29*, 201–208; c) T. Haiwara, K. Taya, Y. Yamamoto, H. Yamazaki, *J. Mol. Catal.* **1989**, *54*, 165–170; d) B. M. Trost, C. A. Merlic, *J. Am. Chem. Soc.* **1990**, *112*, 9590–9600; e) M. Suginome, H. Nakamura, Y. Ito, *Tetrahedron Lett.* **1997**, *38*, 555–558; f) M. Suginome, S.-i. Matsunaga, T. Iwanami, A. Matsumoto, Y. Ito, *Tetrahedron Lett.* **1996**, *37*, 8887–8890; g) S. Braune, U. Kazmaier, *J. Organomet. Chem.* **2002**, *641*, 26–29; h) J. Mancuso, M. Lautens, *Org. Lett.* **2003**, *5*, 1653; i) M. Tanabiki, K. Tscuchiya, Y. Kumanomido, K. Matsubara, Y. Motoyama, H. Nagashima, *Organometallics* **2004**, *23*, 3976–3981; j) D. Villemin, A. Jullien, N. Bar, *Tetrahedron Lett.* **2007**, *48*, 4191–4193.

[6] P. W. N. M. van Leeuwen, P. C. J. Kamer, J. N. H. Reek, P. Dierkes, *Chem. Rev.* **2000**, *100*, 2741–2769.

  

[7] a) A. Dondoni, T. Dall′Occo, G. Fantin, M. Fogagnolo, A. Medici, P. Pedrinia, *Chem. Commun.* **1984**, 258–260; b) A. Dondoni, G. Fantin, M. Fogagnolo, A. Medici, P. Pedrinia, *J. Org. Chem.* **1987**, *52*, 3413–3420; c) S. E. Whitney, B. Rickborn, *J. Org. Chem.* **1991**, *56*, 3058–3063; d) M. C. Pirrung, S. Ghorai, *J. Am. Chem. Soc.* **2006**, *128*, 11772–11773.

[8] a) H. Werner, R. Vicha, A. Gissibl, O. Reiser, *J. Org. Chem.* **2003**, *68*, 10166–10168; b) M. Seitz, A. Kaiser, A. Tereshchenko, C. Geiger, Y. Uematsu, O. Reiser, *Tetrahedron* **2006**, *62*, 9973–9980.

[9] CCDC-743242 (**2b**) and CCDC-743243 (**3b**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

[10] T. Mitsudome, T. Umetani, N. Nosaka, K. Mori, T. Mizugaki, K. Ebitani, K. Kaneda, *Angew. Chem.* **2006**, *118*, 495–499; *Angew. Chem. Int. Ed.* **2006**, *45*, 481–485.

[11] While this manuscript was under revision, a report on the aerobic oxidation of styrene using palladium chloride without cocatalyst appeared. At an ambient pressure of oxygen, very similar results to ours (Table 3, entry 1) were achieved. A. C. Bueno, A. O. de Souza, E. V. Gusevskaya, *Adv. Synth. Catal.* **2009**, DOI: 10.1002/adsc.200900294.

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