A significant effect of anion binding ureas on the product ratio in the palladium(II)-catalyzed hydrocarbonylation of alkenes

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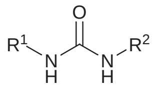
Hydrogen bonding of urea derivatives to the anionic ligands X of (dppp)PdX$_2$ catalysts significantly increases the hydroacylation of cyclopentene relative to the hydroformylation, most probably due to a decreased coordination strength of the anionic ligands.

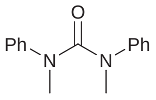
Transition metal complexes are important homogeneous catalysts for alkene polymerization[1] and alkene/CO copolymerization reactions.[2] In the L$_2$PdX$_2$-catalyzed hydrocarbonylation of alkenes with synthesis gas (CO/H$_2$) either aldehydes (hydroformylation), ketones (hydroacylation), or polyketones (copolymerization) are formed. The type of reaction is determined mainly by the coordination strength of the anionic ligands X in L$_2$PdX$_2$.[3] Only Pd^{II} catalysts with weakly coordinating anions (*e.g.* X = TFA) show sufficient activity in such hydrocarbonylation reactions. These catalysts are prepared by anion metathesis reactions of L$_2$PdX$_2$ with the corresponding silver salt (X = Cl)[4] or Brønsted acid (X = OAc).[5] Alternatively, strong Lewis acids like methylalumoxane (MAO)[6] or SnCl$_2$[7] are added.

Our group has developed a variety of anion receptors based on multiple hydrogen bonding to (sulfon)amides[8] or (thio)ureas,[9] or coordination to a Lewis acidic uranyl center.[10] These anion receptors have been applied for anion-selective sensors (CHEMFETs)[11] and in membrane transport studies. Recently, we have described the catalytic activity of anion receptors in acyl transfer reactions.[12]

Here we show that *N,N′*-disubstituted urea derivatives **1**–**5** significantly influence the performance of the (dppp)PdX$_2$ catalyst [dppp = 1,3-bis(diphenylphosphino)propane] in hydrocarbonylation reactions. The effect is attributed to the interaction[13] of the acidic urea protons with the counterions (X = OAc, TFA, OTs) leading to a decrease in their coordination strength. There are reports of hydrogen bonding to the anionic ligands of transition metal complexes in the solid state.[14] To the best of our knowledge this is the first report in which hydrogen bonding to the anionic ligands of a homogeneous catalyst alters the product ratio of the reaction.[15]



1 R^1 = R^2 = Ph
2 R^1 = *p*-F$_3$CC$_6$H$_4$, R^2 = Ph
3 R^1 = R^2 = *p*-F$_3$CC$_6$H$_4$
4 R^1 = Bu^n, R^2 = Ph
5 R^1 = R^2 = Bu^n



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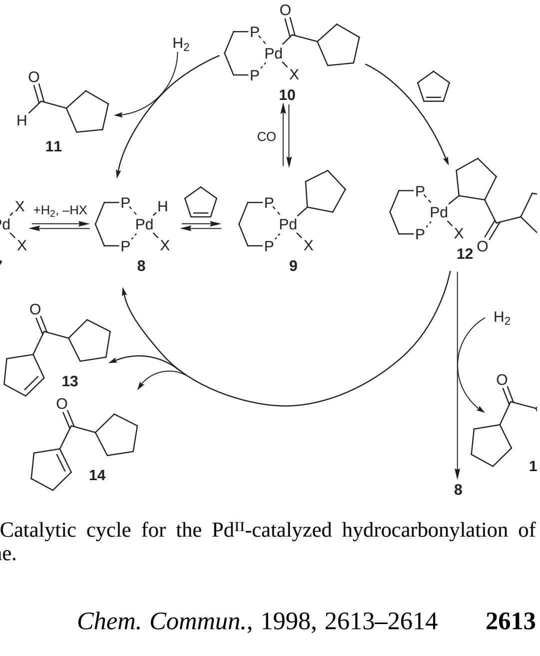
As a model reaction we used the Pd^{II}-catalyzed hydrocarbonylation of cyclopentene with synthesis gas in anisole.† The mechanism for this reaction[3] is depicted in Scheme 1. Hydride **8** is formed by reaction of precatalyst (dppp)PdX$_2$ with H$_2$. The rate of the subsequent exchange reaction of cyclopentene for X depends strongly on the coordination strength of the counterion to the Pd center.[4,16] Migratory insertion gives the σ-alkyl–Pd complex **9** and consecutive CO insertion yields the acyl–Pd intermediate **10**. The formation of **10** from **8** is monitored by the turnover number of CO (TON$_{CO}$), *i.e.* the number of CO insertions per Pd center. Intermediate **10** can react further in two different ways, either giving cyclopentanecarbaldehyde **11** or yielding one of the ketones **13**–**15** after insertion of a second molecule of cyclopentene. In all cases **8** is regenerated either by β-elimination or by oxidative addition of HX to the Pd^0 complex formed.

The selectivity for ketones increases from 14 to 98% reflecting the decrease in coordination strength of the anionic ligands X in the series of (dppp)PdX$_2$ (X = TFA, OMs, OTs, OTf, entries 1–4 in Table 1) with $6.0 \times 10^2 < \mathrm{TON_{CO}} < 9.2 \times 10^2$ mol (mol Pd)$^{-1}$ h^{-1}. With (dppp)Pd(OAc)$_2$ (entry 5) the TON$_{CO}$ is reduced to 0.2×10^2 mol (mol Pd)$^{-1}$ h^{-1} because of the stronger coordinating acetate, and the selectivity for ketones is 24%. Weaker coordinating anions may enhance the (intrinsic) electrophilicity of the Pd^{II} center and, of course, these anions are more easily displaced from the (fourth) coordination site which facilitates the formation of intermediates **10** (increased TON$_{CO}$) and **12** (increased selectivity for ketones).

We found that in the presence of 0.6 mol% [7.5 equiv. with respect to the (dppp)Pd(TFA)$_2$ catalyst] of *N,N′*-diphenylurea **1** the selectivity for ketones increases from 14 to 25% (entry 6 in Table 1), whereas the TON$_{CO}$ increases from 6.0×10^2 to 7.8×10^2 mol (mol Pd)$^{-1}$ h^{-1}.‡ With 0.6 mol% of the urea derivatives **2** and **3**, containing either one or two electron-withdrawing substituents at the phenyl rings that will increase the anion affinity of the urea moiety,[17] the selectivity for ketones shows a sharp increase from 14 to 49 and 61%, respectively (entries 7 and 8). In both cases the TON$_{CO}$ is similar to that in the presence of urea **1**. Both *N*-butyl-*N′*-phenylurea **4** and *N,N′*-dibutylurea **5** do not significantly change the selectivity for ketones (entries 9 and 10), which is in accordance with the much lower acidity and anion binding strength of (di)alkyl ureas compared to diaryl ureas.[18]

The altered selectivities of the catalyst upon addition of diarylureas **1** or **3** were also observed for the catalysts



Scheme 1 Catalytic cycle for the Pd^{II}-catalyzed hydrocarbonylation of cyclopentene.

Table 1 Selectivity for ketones and turnover number for the hydrocarbonylation of cyclopentene with CO and H_2 in the presence of urea derivatives **1**–**6**[a]

Entry	Anion	Receptor[b]	Selectivity (%)[c]	$TON_{CO}/10^2$ mol (mol Pd)$^{-1}$ h^{-1} [d]
1	OTf	—	98	8.7
2	OTs	—	54	8.2
3	OMs	—	41	9.2
4	TFA	—	14	6.0
5	OAc	—	24	0.2
6	TFA	**1**	25	7.8
7	TFA	**2**	49	7.8
8	TFA	**3**	61	8.3
9	TFA	**4**	16	5.9
10	TFA	**5**	10	5.1
11	OAc	**1**	45	0.4
12	OAc	**3**	80	0.4
13	OTs[e]	**1**	82	7.0
14	OTs	**3**	95	10
15	TFA	**6**	14	6.4
16	TFA[f]	**6**	12	5.8
17	OAc	**6**	25	0.3
18	OTs	**6**	51	9.6

[a] Cyclopentene (5 ml), anisole (10 ml), (dppp)PdX_2 (0.08 mol%), 110 °C, 80 bar (CO:H_2 = 1:1), analysis by GC FID, integrals were not corrected for sensitivities. [b] 7.5 equiv. cocatalyst compared to Pd catalyst. [c] Percentage of hydroacylation products (**13–15**) of the total amount of products formed, accuracy ±2%. [d] Turnover number of CO determined as the sum of TONs of all products **11**, **13**, **14** and **15**; accuracy ±5% (see note ¶). [e] 10 equiv. cocatalyst **5**. [f] 13 equiv. cocatalyst **6**.

(dppp)Pd$(OAc)_2$ (entries 11 and 12) and (dppp)Pd$(OTs)_2$ (entries 13 and 14). In both cases the stronger anion binding urea **3** causes the largest change in the selectivity for ketones, *i.e.* from 24 to 80% for (dppp)Pd$(OAc)_2$ and from 54 to 95% for (dppp)Pd$(OTs)_2$. The TON_{CO} is enhanced from 0.2×10^2 to 0.4×10^2 and from 8.2×10^2 to 10×10^2 mol (mol Pd)$^{-1}$ h^{-1}, respectively. These results suggest that the observed increase in ketone formation is the result of complexation of the anionic ligands by the urea derivatives **1**–**3** *via* hydrogen bonding which decreases the coordination strength of the counterions to the Pd center.

Experiments carried out in the presence of a large excess of tetrasubstituted urea **6**, which is unable to bind anions *via* hydrogen bonding, show that neither the selectivity for ketones nor the TON_{CO} is affected to a significant extent (entries 15–18 in Table 1). This excludes the possibility that the observed effect is due to coordination of the urea carbonyl to the Pd center or to a change in the polarity of the reaction medium.§

Our results show that hydrogen bond formation to the anionic ligands X of (dppp)Pd catalysts can significantly change the selectivity of the catalyst in the hydrocarbonylation of cyclopentene with synthesis gas. Addition of *N*,*N*′-diarylureas **1**–**3** strongly favours hydroacylation with respect to hydroformylation. The maximum effect is observed with the stronger anion binding urea **3**.

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Notes and references

† *Experimental procedure*: Hydrocarbonylation experiments were performed in a 100 ml autoclave at 110 °C. 10 ml anisole, 5 ml cyclopentene, 0.08 mol% of (dppp)PdX_2 catalyst, and urea cocatalyst were brought under a H_2 atmosphere whereafter the autoclave was pressurized with 40 bar CO and 40 bar H_2. After a reaction time of 20 h the autoclave was cooled down and the gas (pressure drop < 15 bar) was vented off. The products were analysed by GC FID (CPSIL-5, 50 m).

‡ The amount of added *N*,*N*′-diphenylurea **1** correlates well with the selectivity for ketones formed in the reaction and the TON_{CO}. With varying amounts (2–18 equiv.) of **1** as cocatalyst in the (dppp)Pd$(TFA)_2$ catalyzed reaction both the selectivity for ketones and the TON_{CO} are increased. A maximum of 37% and 8.9×10^2 mol (mol Pd)$^{-1}$ h^{-1} was reached with 1.5 mol% (18 equiv.) of **1** (limited by the solubility of **1** in the reaction medium).

§ Additional evidence for hydrogen bond formation of **1**–**5** to the anionic ligands X of (dppe)PdX_2 (X = Cl, TFA, OTs) was obtained by IR, ^{1}H and ^{31}P NMR spectroscopic studies in $CDCl_3$ at room temperature (ref. 19). Addition of 2 equiv. (dppe)PdCl_2 to an 1 mM solution of *N*,*N*′-diphenylurea **1** (free N–H vibration at 3422 cm^{-1}) gave rise to an additional N–H stretch frequency at 3330 cm^{-1} in the FT–IR spectrum. The ^{1}H NMR spectra of ureas **1**–**5** show in all cases downfield shifts ($0.40 > \Delta\delta > 0.15$ ppm) for the urea proton signals upon addition of 1 equiv. of (dppp)PdX_2, which is indicative for hydrogen bond formation. Furthermore the ^{31}P NMR resonances of the (dppe)PdX_2 complexes shift over 1 ppm downfield upon addition of 2 equiv. of **1**. Similar downfield shifting of the ^{31}P NMR resonances is also observed upon weakening of the coordination strength of the anions of (dppe)PdX_2 (X = TFA: δ 63.1; X = OTs: δ 69.9). In contrast to this the addition of 1,3-dimethyl-1,3-diphenylurea **6** to the Pd complexes did not induce any significant shift of the ^{31}P NMR resonances.

¶ The TONs based on conversion of cyclopentene ($TON_=$).can easily be calculated from Table 1 according to $TON_= = TON_{CO} \times (1 + \text{selectivity})$.

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