Tetrahedron Letters 54 (2013) 2209-2211

Contents lists available at SciVerse ScienceDirect

**Tetrahedron Letters** 

journal homepage: www.elsevier.com/locate/tetlet

# Rhodium catalyzed hydroformylation with formal dehyde and an external $\rm H_2\mathchar`-source$

Marcus Uhlemann<sup>a</sup>, Stephan Doerfelt<sup>b</sup>, Armin Börner<sup>a,c,\*</sup>

<sup>a</sup> Leibniz-Institut für Katalyse an der Universität Rostock e.V., Albert-Einstein Straße 29a, 18059 Rostock, Germany <sup>b</sup> Miltitz Aromatics GmbH, PF 1355, 06756 Bitterfeld-Wolfen, Germany <sup>c</sup> Institut für Chemie der Universität, Rostock A.-Einstein-Str. 31, 18059 Rostock, Germany

#### ARTICLE INFO

Article history: Received 3 January 2013 Revised 13 February 2013 Accepted 15 February 2013 Available online 24 February 2013

Keywords: Hydroformylation Olefin Rhodium Formaldehyde Hydrogen

#### Introduction

The hydroformylation of olefins, that means the addition of CO and H<sub>2</sub> (syngas) to olefins, is one of the largest homogeneously catalyzed reaction in industries.<sup>1</sup> In this respect exclusively catalysts on the basis of cobalt and rhodium are used. They are frequently modified by trivalent phosphorus compounds as ligands. Annually more than 10 million tons of aldehydes are produced by this methodology.<sup>2</sup> It is interesting to note, that with the exception of some products in pharmaceutical, agrochemical, and fragrance industry,<sup>3</sup> the reaction is mainly employed for the large-scale production of bulk chemicals. Besides the high price of the catalyst (rhodium) the work with highly toxic and gaseous CO is another argument against the use of this reaction in academic labs and for the manufacturing of fine chemicals. Meanwhile also the increasing price for CO may decide upon the economy of small scale hydroformylations. Non-toxic and cheap substitutes for syngas would overcome these problems.<sup>4</sup> One of the most promising alternatives is represented by paraformaldehyde or an aqueous solution of formaldehyde (formalin) in combination with a phosphorus modified Rh-catalyst.<sup>5</sup> The catalyst must be active in the decarbonylation of formaldehyde as well as in the hydroformylation of the olefin.

Up to now most efforts have been dedicated to the optimization of the catalysts. Thus, for the decarbonylation of aldehydes Rh-

ABSTRACT

The efficiency of the syngas-free rhodium catalyzed hydroformylation of olefins with formaldehyde can be significantly improved by the addition of hydrogen gas or formic acid. © 2013 Elsevier Ltd. All rights reserved.

> complexes based on tripodal triphosphines have been suggested.<sup>6</sup> Rosales et al. gave evidence that in strong contrast to the hydroformylation with syngas a double excess of bidentate phosphorus ligands in comparison to rhodium supports the decomposition of paraformaldehyde as well as the subsequent hydroformylation reaction.<sup>7</sup> Recently, Morimoto and co-workers showed that a combination of two catalysts. Rh-BINAP and rhodium complexes bearing Xantphos-type ligands, can efficiently mediate the reaction with formaldehyde in toluene.<sup>8</sup> They assumed that the former catalyst decomposes formaldehyde to give syngas and the second immediately utilizes it for the hydroformylation of the olefin. Under these conditions several aldehydes could be produced in good yields and excellent n-regioselectivity within 20 h. A similar catalytic mechanism as suggested for the hydroformylation with syngas was suggested. In addition, Taddei and co-workers noted that the reaction can be accelerated by the effect of microwaves.<sup>9</sup>

etrahedro

Bearing the known dependency of some Rh-catalyzed hydroformylations with syngas on the hydrogen partial pressure in mind,<sup>10</sup> we investigated the reaction with formaldehyde in the presence of hydrogen gas (Scheme 1). We had hoped that the competing hydrogenation of the starting olefin can be suppressed.

# **Results and discussion**

Reactions with formaldehyde (37 % aqueous solution) were conducted at 10 bar  $H_2$  in a 25 mL reactor. In first trials the precatalyst was prepared by reaction of [{Rh(cod)}<sub>2</sub>( $\mu$ -Cl)<sub>2</sub>] with BINAP.



<sup>\*</sup> Corresponding author. Tel.: +49 381 1281 202; fax: +49 381 1281 51202. *E-mail address:* armin.boerner@catalysis.de (A. Börner).

<sup>0040-4039/\$ -</sup> see front matter © 2013 Elsevier Ltd. All rights reserved. http://dx.doi.org/10.1016/j.tetlet.2013.02.049



Scheme 1. Hydroformylation with formaldehyde in the presence of hydrogen gas.

#### Table 1

Rh-catalyzed hydroformylation of 1-octene with formaldehyde/H $_{\rm 2}$  with BINAP as ligand  $^{\rm a}$ 

| Run | Solvent | pH <sub>2</sub><br>(bar) | Conv. <sup>b</sup><br>(%) | Yield <sup>b</sup><br>(%) | l/b <sup>b</sup> | Isom. <sup>b,c</sup><br>(%) | Octane <sup>b</sup><br>(%) |
|-----|---------|--------------------------|---------------------------|---------------------------|------------------|-----------------------------|----------------------------|
| 1   | Toluene | _                        | 34                        | 30                        | 1.8              | 4                           | _                          |
| 2   | Toluene | 10                       | 79                        | 69                        | 3.9              | 5                           | 5                          |
| 3   | THF     | -                        | 27                        | 23                        | 1.9              | 4                           | -                          |
| 4   | THF     | 10                       | 59                        | 56                        | 2.4              | 2                           | 1                          |
|     |         |                          |                           |                           |                  |                             |                            |

<sup>a</sup> Conditions: [1-octene] = 1 M; 1.2 equiv formaldehyde, [{Rh(cod)}<sub>2</sub>( $\mu$ -Cl)<sub>2</sub>]/BIN-AP/1-octene = 1:4:1000, 90 °C, solvent, 6 h.

<sup>b</sup> Determined by GC.

<sup>c</sup> Contained mainly isomerized olefins and traces of other internal aldehydes.

1-Octene was used as the substrate at 90 °C in toluene. To our delight, we found that results obtained under these conditions were superior to those obtained without hydrogen gas (Table 1).

Thus, within 6 h reaction time, conversion of olefin and yield of the desired aldehyde could be almost doubled in comparison to the parent set-up (Table 1, runs 1 and 2). Interestingly also a considerable increase in *n*-regioselectivity was found. The degree of isomerization of the starting olefin was almost the same under both conditions. Only a small amount of octane as a product of the hydrogenation was produced under hydrogen. Similar results were obtained in THF as the solvent. Since THF has some disadvantages in industrial scale, all subsequent trials were performed in toluene.

In the next attempts we investigated the effect of phosphorus ligands. The reaction time was shortened to 2 h and the temperature was increased to 120 °C. Table 2 clearly shows that also dppp [1,3-bis(diphenylphosphino)propane] and dppf [1,1'-bis(diphenylphosphino)ferrocene] can be advantageously used as ligands instead of BINAP. In all instances in comparison to the reaction

without  $H_2$  significantly improved conversion, yield of desired aldehyde, and *n*-regioselectivity could be achieved. That means turnover numbers (TON) as well as turnover frequencies (TOF) were ca. two- or threefold higher than without hydrogen. Also in comparison to the trial where syngas (ratio CO/H<sub>2</sub> = 1:1, 10 bar) instead of formaldehyde was used (Table 2, run 7), a dramatic improvement of reactivity and selectivity was noted. With dppf as the ligand an extremely high *n*-regioselectivity of 25 was obtained (run 9). In order to elucidate, whether also other hydrogen sources can be used, formic acid was added to the reaction (Table 2, runs 10–12). Also under these conditions with all three catalysts the reaction with formaldehyde is clearly supported. But in comparison to the reaction with hydrogen gas a higher isomerization tendency of the starting olefin was found.

To investigate the scope of the new method in the subsequent trials also other olefins were subjected to these reaction conditions (Table 3).

By using a Rh(dppp) catalyst without exception with all substrates improved reaction rates were achieved in comparison to the reaction without hydrogen gas. This holds especially for the reaction with styrenes (runs 1–10). Remarkably, a decrease of the l/b-ratio yielded under the new conditions. With allylbenzene a strong isomerization activity was noted, also in the absence of hydrogen gas and the yield of the desired aldehyde was low (Table 3, runs 15 and 16). *N*-Vinylphthalimide and butylacrylate suffered partial hydrogenation (runs 18 and 20).

Finally, the reactions were scaled-up in a 1 L batch reactor under a reduced  $H_2$ -pressure of 5 bar. Under this modified technical setup the rate accelerating effect of hydrogen on the hydroformylation remained clearly visible, but now isomerization of the starting olefin became a side reaction to some extent (e.g., with 1-octene: 17%).

## Summary and conclusion

In conclusion, a new protocol for the syngas-free hydroformylation has been discovered, which should be particularly useful for the production of aldehydes on a small scale. Pivotal aspect is that for the acceleration of the reaction and for the improvement of the regioselectivity additional hydrogen sources like gaseous hydrogen or formic acid are used.<sup>11</sup> We assume that hydrogen supports the hydrogenolysis of the Rh-acyl complex in a late stage of the catalytic cycle.<sup>12</sup>

#### **Experimental section**

Typical procedure for the hydroformylation.

#### Table 2

Rh-catalyzed hydroformylation with 1-octene with formaldehyde/H2 using different P-ligands<sup>a</sup>

| ······································ |        |                       |                        |                          |                  |                          |            |  |
|--|--------|-----------------------|------------------------|--------------------------|------------------|--------------------------|------------|--|
| Run                                    | Ligand | pH <sub>2</sub> (bar) | Conv. <sup>b</sup> (%) | Yield <sup>b,c</sup> (%) | l/b <sup>b</sup> | Isom. <sup>b,d</sup> (%) | Octane (%) |  |
| 1                                      | BINAP  | _                     | 30                     | 28                       | 1.9              | 2                        | _          |  |
| 2                                      | BINAP  | 10                    | 81                     | 72                       | 2.3              | 8                        | 1          |  |
| 4                                      | dppp   | -                     | 38                     | 32                       | 1.3              | 5                        | 1          |  |
| 5                                      | dppp   | 10                    | 84                     | 68                       | 1.3              | 11                       | 5          |  |
| 7                                      | dppp   | e                     | 26                     | 26                       | 1.0              | -                        | -          |  |
| 8                                      | dppf   | -                     | 46                     | 25                       | 6.5              | 20                       | 1          |  |
| 9                                      | dppf   | 10                    | 93                     | 55                       | 25.0             | 22                       | 16         |  |
| 10                                     | BINAP  | f                     | 68                     | 59                       | 2.1              | 8                        | 1          |  |
| 11                                     | dppp   | f                     | 97                     | 68                       | 1.4              | 24                       | 5          |  |
| 12                                     | dppf   | f                     | 75                     | 40                       | 6.9              | 33                       | 2          |  |

<sup>a</sup> Conditions: [1-octene] = 0.5 M, 1.2 equiv formaldehyde, [Rh(cod)<sub>2</sub>(µ-Cl)<sub>2</sub>]/ligand/1-octene = 1:4:1000, 120 °C, toluene.

<sup>b</sup> Determined by GC.

<sup>c</sup> Yield of aldehydes.

<sup>d</sup> Contained mainly isomerized olefins and traces of other internal aldehydes.

<sup>e</sup> 2 h, without formaldehyde, but with syngas (CO/H<sub>2</sub> = 1/1, 10 bar).

 $^{\rm f}\,$  Without hydrogen gas, but with formic acid (1.0 equiv).

| Table 3   |
|---|
| Rh(dppp)-catalyzed hydroformylation of different olefins with formaldehyde/H $_2^a$ |

| Run | Olefin                          | pH <sub>2</sub> (bar) | Conv. <sup>b</sup> (%) | Yield <sup>b,c</sup> (%) | $1/b^{b}$ | Isom. <sup>b,d</sup> (%) | Hydr. (%) |
|-----|---------------------------------|-----------------------|------------------------|--------------------------|-----------|--------------------------|-----------|
| 1   | Styrene                         | -                     | 23                     | 23                       | 1.1       | _                        | _         |
| 2   | Styrene                         | 10                    | 91                     | 83                       | 0.6       | -                        | 8         |
| 4   | 4-Cl-styrene                    | _                     | 14                     | 14                       | 0.8       | -                        | _         |
| 5   | 4-Cl-styrene                    | 10                    | 81                     | 76                       | 0.5       | -                        | 5         |
| 7   | 4-MeO-styrene                   | -                     | 13                     | 13                       | 0.6       | -                        | -         |
| 8   | 4-MeO-styrene                   | 10                    | 77                     | 74                       | 0.4       | -                        | 3         |
| 9   | 4- <i>t</i> Bu-styrene          | -                     | 11                     | 11                       | 0.7       | -                        | -         |
| 10  | 4- <i>t</i> Bu-styrene          | 10                    | 82                     | 78                       | 0.5       | -                        | 4         |
| 11  | Cyclooctene                     | -                     | <1                     | <1                       | -         | -                        | -         |
| 12  | Cyclooctene                     | 10                    | 7                      | 7                        | -         | -                        | -         |
| 13  | 3,3-Dimethyl-1-butene           | -                     | 61                     | 61                       | 11        | -                        | -         |
| 14  | 3,3-Dimethyl-1-buten            | 10                    | 88                     | 85                       | 22        | -                        | 3         |
| 15  | Allylbenzene                    | -                     | 90                     | 1                        | 2.3       | 89                       | -         |
| 16  | Allylbenzene                    | 10                    | 99                     | 2                        | 2.1       | 96                       | 1         |
| 17  | N-Vinylphthalimide <sup>e</sup> | -                     | 11                     | 6                        | 0.7       | -                        | 5         |
| 18  | N-Vinylphthalimide <sup>e</sup> | 10                    | 46                     | 28                       | 0.1       | -                        | 18        |
| 19  | Butylacrylate                   | -                     | 2                      | -                        | -         | -                        | 2         |
| 20  | Butylacrylate                   | 10                    | 71                     | 17                       | 3.7       | 12 <sup>f</sup>          | 38        |

<sup>a</sup> Conditions: [olefin] = 0.5 M, 1.2 equiv formaldehyde, [{Rh(cod)}<sub>2</sub>(µ-Cl)<sub>2</sub>]/dppp/olefin = 1:4:1000, 120 °C, toluene, 20h reaction time.

<sup>b</sup> Determined by GC.

<sup>c</sup> Yield of aldehyde.

<sup>d</sup> Contained mainly isomerized olefins or other internal aldehydes (see also footnote f).

<sup>e</sup> *N*-Vinylphthalimid = 0.05 M.

<sup>f</sup> Concerns alcohols formed.

[{Rh(cod)}<sub>2</sub>( $\mu$ -Cl)<sub>2</sub>] (5  $\mu$ mol), phosphorus ligand (20  $\mu$ mol), and solvent (6.3 mL) were added to a pressure reactor (25 mL). After addition of formaldehyde (37 % in H<sub>2</sub>O, 6 mmol) and substrate (5 mmol) the reaction mixture was purged with nitrogen for several times and heated with stirring (1000 rpm) to the indicated reaction temperature. Once the desired temperature was achieved, H<sub>2</sub> was introduced and the reaction mixture was stirred for the indicated reaction time. After cooling to room temperature the gas was released and the reaction mixture was again purged with nitrogen. Dodecane was added as an internal standard and brine in order to separate the phases. The organic phase was finally analyzed by GC.

#### Acknowledgments

We acknowledge financial support by AiF Projekt GmbH und stimulating discussions with Mr. J. Jimenez Pinto (Bitterfeld-Wolfen), Dr. J. Norinder, and Dr. D. Selent (Rostock).

# **References and notes**

 (a)Rhodium Catalyzed Hydroformylation; van Leeuwen, P. W. N. M., Claver, C., Eds.; Kluver Academic Publishers: Dordrecht, Netherlands, 2000; (b) Franke, R.; Selent, D.; Börner, A. Chem. Rev. 2012, 112, 5675.

- Process Economics Program Report 21E OXO ALCOHOLS, Syed Naqvi, SRI Consulting, Menlo Park, California 94025, USA, 2010.
- 3. Whiteker, G. T.; Cobley, C. Top. Organomet. Chem. 2012, 42, 35.
- 4. Morimoto, T.; Kakiuchi, K. Angew. Chem., Int. Ed. 2004, 43, 5580.
- (a) Ahn, H. S.; Han, S. H.; Uhm, S. J.; Seok, W. K.; Lee, H. N.; Korneeva, G. A. J. Mol. Catal. A: Chem. 1999, 144, 295; (b) Okano, T.; Kobayashi, T.; Konishi, H.; Kiji, J. Tetrahedron Lett. 1982, 23, 4967.
- (a) Beck, C. M.; Rathmill, S. E.; Park, Y. J.; Chen, J.; Crabtree, R. H.; Liable-Sands, L. M.; Rheingold, A. L. Organometallics **1999**, *18*, 5311; (b) Kreis, M.; Palmelund, A.; Bunch, L.; Madsen, R. Adv. Synth. Catal. **2006**, 348, 2148.
- (a) Rosales, M.; Arrieta, F.; Baricelli, P.; Gonzalez, A.; Gonzalez, B.; Guerrero, Y.; Moratinos, C.; Pacheco, I.; Perez, H.; Urdaneta, J. *Catal. Lett.* **2008**, *126*, 367; (b) Rosales, M.; Gonzáles, A.; Gonzáles, B.; Moratinos, C.; Pérez, H.; Urdaneta, J.; Sánchez-Delgado, R. A. J. Organomet. Chem. **2005**, 690, 3095.
- Makado, G.; Morimoto, T.; Sugimoto, Y.; Tsutsumi, K.; Kagawa, N.; Kakiuchi, K. Adv. Synth. Catal. 2010, 352, 299.
- 9. Airiau, E.; Gerard, N.; Mann, A.; Salvadori, J.; Taddei, M. Synlett 2011, 199.
- (a) Kubis, Ch.; Selent, D.; Sawall, M.; Ludwig, R.; Neymeyr, K.; Baumann, W.; Franke, R.; Börner, A. *Chem. Eur. J.* **2012**, *18*, 8780; (b) Kubis, C.; Ludwig, R.; Sawall, M.; Neymeyr, K.; Börner, A.; Wiese, K.-D.; Hess, D.; Franke, R.; Selent, D. *ChemCatChem* **2010**, *2*, 287.
- 11. When we tested the dual system consisting of two different catalysts described in Ref. 8 under our conditions, no rate accelerating effect on the hydroformylation was observed.
- 12. Preliminary spectroscopic investigations did not give clear experimental support for this hypothesis, in particular with respect to observations described in Ref. 10. Probably the hydroformylation with formaldehyde proceeds via a different mechanism in comparison to the reaction with syngas. Therefore more detailed kinetic investigations are scheduled.