SELECTIVE HYDRATION OF FERROCENYLETHYNE MEDIATED BY A PALLADIUM COMPLEX WITH A CAMPHORHYDRAZONE LIGAND

Jiří TAUCHMAN[a1], M. Fernanda N. N. CARVALHO[b] and Petr ŠTĚPNIČKA[a2,*]

[a] *Charles University in Prague, Faculty of Science, Department of Inorganic Chemistry, Hlavova 2030, 128 40 Prague 2, Czech Republic; e-mail:* [1] *tauchman@natur.cuni.cz,* [2] *stepnic@natur.cuni.cz*

[b] *Centro de Química Estrutural, Complexo I, Instituto Superior Técnico, Universidade Técnica de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal; e-mail: fcarvalho@ist.utl.pt*

Received June 24, 2011
Accepted August 29, 2011
Published online September 30, 2011

Complex $[PdCl_2L_2]$, where L is a camphor hydrazone ligand, (1*R*,4*S*)-1,7,7-trimethyl-3-(2,2-dimethylhydrazone)-bicyclo[2.2.1]heptane-2,3-dione, efficiently promotes Markovnikov hydration of ethynylferrocene to acetylferrocene in aqueous methanol at room temperature. 1-Ferrocenylprop-1-yne and simple organic alkynes such as 1-octyne or ethynylbenzenes are not affected or polymerize under the reaction conditions.
Keywords: Palladium; Alkynes; Camphor-derived ligands; Ferrocene; Hydration.

Studies into interactions between transition metal complexes and alkynes are of utmost importance as they provide a basis for a subsequent synthetic utilization of transition metal-mediated reactions of alkynes as reactive hydrocarbon substrates[1]. In this regard, transition metal-catalyzed hydrations of alkynes are no exception providing an access to synthetically extremely versatile carbonyl compounds. In addition, the metal-catalyzed hydration reactions represent convenient practical alternatives to conventional reactions that are typically performed under the action of toxic and hazardous reagents or under harsh reaction conditions[2,3].

We have recently demonstrated that palladium(II) complexes with camphor-derived ligands promote [2+2+2]-cyclotrimerization of internal alkynes[4] and cyclization reactions of pentynols[5]. This and other our recent studies on transition metal-catalyzed cyclotrimerization reactions of ethynylferrocenes[6] prompted us to extend our previous work and examine the reactivity of Pd(II) complexes possessing camphor-based ligands[7] (compounds **1** and **2** in Chart 1) toward ethynylferrocene and 1-ferrocenylprop-1-yne as possible sources of the redox-active ferrocenyl moiety[8].

doi:10.1135/cccc2011130

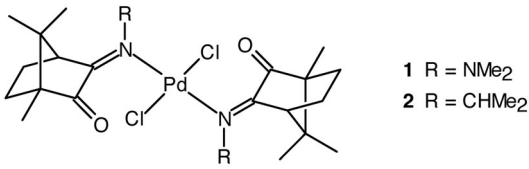
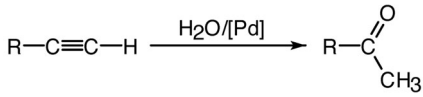


Chart 1

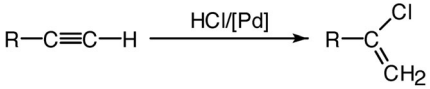
RESULTS

The initial reaction tests were rather disappointing since the reaction of complex **1** (25 mole %) with ethynylferrocene in dry dichloromethane led to a partial decomposition of the palladium(II) complex to palladium black and free camphor hydrazone ligand, and to a formation of FcC(Cl)=CH_2 (Fc = ferrocenyl) and some intractable polymeric products. When complex **2** was reacted similarly with FcC≡CH, the alkyne was recovered unchanged. Complexes **1** and **2** also did not appreciably react with FcC≡CCH_3 under similar conditions.

The situation changed upon changing the reaction solvent to "dry" methanol (distilled from a solution of sodium methoxide). In this solvent, ethynylferrocene was converted to acetylferrocene (Scheme 1; R = Fc) upon reacting with complex **1** (25 mole %) within 20 h. Similarly to previous cases, the complex partly decomposed during the reaction, yielding palladium black and the camphorhydrazone ligand, which contaminated the soluble reaction product (acetylferrocene). The reaction with camphorimine complex **2** in methanol proceeded similarly to afford a mixture acetylferrocene (98%) as the hydration product, and FcC(Cl)=CH_2 (2%), which apparently results, by addition of HCl formed by solvolytic equilibria, in the reaction mixture (Scheme 2). In addition to unreacted **2**



Scheme 1
General scheme of the hydration reaction. R and [Pd] source are specified in the text



Scheme 2
Side-reaction resulting in the formation of the 1-chlorovinyl derivatives. R and [Pd] source are specified in the text

and some palladium black, the insoluble part of the reaction mixture contained some unidentified polymeric material in this case.

In view of its practical usefulness, we focused on the hydration reaction and tried to optimize reaction conditions using complex **1** as the pre-catalyst (Table I). It was found that acetylferrocene is obtained in a 70% isolated yield from a reaction with 25 mole % catalyst in "dry" methanol. Lowering the amount of catalyst expectedly reduced the amount of the hydration product (46% with 5 mole % of Pd). However, when the amount of water in the reaction medium was purposely increased, the yield of acetylferrocene increased to 55% isolated yield for a 1:99 (v/v) and to 74% for a 10:90 (v/v) water–methanol mixture at 5 mole % metal loading.

TABLE I
Summary of initial reaction tests in methanol

Catalyst **1** mole %	Product – Isolated yields, %		Recovered FcC≡CH, %
	$FcCOCH_3$	$FcC(Cl)=CH_2$	
25[a]	70	7	0
10[a]	60	4	1
5[a]	46	4	22
1[a]	20	1	65
5[b]	55	5	18
5[c]	74	5	6

[a] Reaction in "dry" methanol. [b] Reaction in MeOH–H_2O 99:1 (v/v). [c] Reaction in MeOH–H_2O 90:10 (v/v).

Next, we decided to include more alkyne substrates in testing (Table II). Rather surprisingly, the catalytic system studied failed to promote hydration of simple organic alkynes such as 1-octyne, ethynylbenzene and its derivatives substituted at the benzene ring. In order to determine whether ethynylferrocene is required during a kind of a pre-catalytic activation step, we performed two additional reactions with 1:1 mixtures of ethynylferrocene and a simple alkyne (Table II). Even in these cases, only ethynylferrocene underwent hydration. The reaction of an equimolar mixture of PhC≡CH and FcC≡CH with complex **1** (5 mole %) in 90% methanol yielded a mixture of acetylferrocene, liberated camphorhydrazone ligand and traces of $FcC(Cl)=CH_2$, while ethynylbenzene was completely converted to a polymeric material. Similar reaction with a 1:1 mixture of $CH_3(CH_2)_5C\equiv CH$ and

FcC≡CH produced a mixture of acetylferrocene, free camphorhydrazone ligand, FcC(Cl)=CH_2 (traces) and unreacted 1-octyne.

TABLE II
Attempted reactions with other terminal alkynes[a]

R in RC≡CH	Composition of the reaction mixture[b]
Ph	ligand, polymer and trace of RAc
4-$CF_3C_6H_4$	ligand and polymer
4-$CH_3OC_6H_4$	ligand, unreacted alkyne and trace of RAc
$CH_3(CH_2)_5$	ligand, unreacted alkyne and trace of RAc
Fc and Ph	ligand, FcAc, trace of FcC(Cl)=CH_2 and polymer from PhC≡CH
Fc and $CH_3(CH_2)_5$	ligand, FcAc, trace of FcC(Cl)=CH_2 and unreacted alkyne

[a] Reactions with 5 mole % of complex **1** in 90% methanol (v/v). [b] Results of NMR analysis. Trace 1–2%.

DISCUSSION AND CONCLUSION

Palladium(II) complex **1** efficiently promotes hydration of ethynylferrocene in wet methanol. Although the hydration reaction competes with polymerization of the starting alkyne and is accompanied by a decomposition of the catalyst, it still mainly produces acetylferrocene as a Markovnikov addition product. It is noted that traces of water that are notoriously present in methanol distilled from sodium methoxide[9] are sufficient for the hydration reaction to proceed efficiently. However, the best results are obtained in intentionally prepared water–methanol mixtures. Changing the solvent to dichloromethane as a hydrophobic solvent or the use of complex **2** (in methanol) assists the formation of FcC(Cl)=CH_2 as an unwanted product of HCl addition, albeit still in trace amounts. 1-Ferrocenylprop-1-yne remains unaffected by complex **1** in either of the tested solvents. Simple aliphatic and aromatic terminal alkynes do not react with complex **1** or are polymerized, which makes this complex a selective and efficient catalyst for selective hydration of ethynylferrocene.

The observed reactivity pattern is tentatively attributed to a hitherto unknown cooperative effect established between the terminal alkyne (FcC≡CH) and the camphor ligand, which assists coordinative activation of the unsaturated substrate. The higher acidic character of ethynylferrocene compared to other alkynes may promote the labilization of the hydrazone ligand in **1** during a specific metal–alkyne interaction and may thus facilitate generation

of a vacant site available for coordination-induced activation of the alkyne. In the absence of alkyne proton (e.g., in 1-ferrocenylprop-1-yne), such activation is obviously impossible and the hydration reaction does not proceed. However, the basic character of camphorimine ligands in **1** and **2** may also play a substantial role as it was already demonstrated for cycloisomerization reactions of alkynols[5]. A pronounced synergistic influence of a basic N-donor group was noted also in hydration reactions of alkynes catalyzed by Ru-complexes with pyridylphosphine ligands and related donors[10]. It remains unclear why H_2O or MeOH do not promote camphorimine labilization as conventional proton sources. In the absence of the alkyne, the solution of complex **1** in wet methanol remains unchanged even after standing for long periods.

EXPERIMENTAL

Materials and Methods

All reactions were performed in the air in sealed reaction vessels. Complexes **1**[7] and **2**[4b], ethynylferrocene[11] and 1-ferrocenylprop-1-yne[12] were prepared by the literature methods. Dichloromethane was dried over $CaCl_2$ and distilled under dinitrogen. Methanol was distilled from a solution of sodium methoxide prepared by dissolving sodium metal in commercial methanol (ca. 1 g/1 l). Solvents for chromatography were used as received (Lach-Ner).

NMR spectra were measured on Varian UNITY Inova 400 or Bruker Avance II$^+$ 400 spectrometers at 25 °C. Chemical shifts (δ, ppm) are given relative to internal $SiMe_4$ (^{1}H and ^{13}C). The compounds were identified by comparing their spectra with those of an authentic sample (acetylferrocene) or with the literature data (FcC(Cl)=CH_2[13]). GC-MS analysis supported the formulation.

Screening Experiments

Complex **1** (30 mg, 0.05 mmol) and ethynylferrocene (42 mg, 0.20 mmol) were reacted in dichloromethane (6 ml) overnight (20 h). The resulting solution was separated from a dark solid formed and evaporated under reduced pressure. Analysis of the evaporation residue by ^{1}H NMR spectroscopy revealed the presence of liberated camphorhydrazone ligand and acetylferrocene. The solid contained complex **1** and some polymeric material. When the reaction was performed in methanol (6 ml), a mixture of free camphorhydrazone ligand and FcC(Cl)=CH_2 was obtained as the soluble product. Under identical conditions, analogous reactions with complex **2** afforded either unchanged ethynylferrocene (in dichloromethane) or a mixture of acetyl ferrocene and FcC(Cl)=CH_2 in ca. 98:2 ratio (in methanol).

Catalytic Tests

Optimization of the reaction conditions. Complex **1** and ethynylferrocene (42 mg, 0.20 mmol) were suspended in methanol (5 ml). The resulting mixture, which immediately turned dark, was stirred in the dark at room temperature for 20 h and then evaporated

under reduced pressure. The dark residue was purified by chromatography over silica gel using hexane–diethyl ether 4:1 (v/v) as the eluent to afford yellow bands (in order of decreasing R_F) containing unreacted ethynylferrocene, (1-chlorovinyl)ferrocene and an orange band of acetylferrocene. Identity and purity of all compounds were confirmed by ^{1}H NMR spectra. The results are summarized in Table I.

Screening of alkyne substrates. Complex **1** (6 mg, 0.01 mmol, 5 mole %) and alkyne (0.2 mmol or 2 × 0.1 mmol in the case of alkyne mixtures) were mixed with aqueous methanol (MeOH–H_2O 90:10 (v/v), 5 ml). The dark mixture was stirred at room temperature in the dark for 20 h and then evaporated under reduced pressure. The residue was analyzed by ^{1}H NMR spectroscopy. The results are presented in Table II.

This work is a part of the long-term research projects of the Faculty of Science, Charles University in Prague that are supported by the Ministry of Education, Youth and Sports of the Czech Republic (project LC06070 and MSM0021620857).

REFERENCES

1. a) Diederich F., Stang P. J., Tykwinski R. R. (Eds): *Acetylene Chemistry: Chemistry, Biology, and Material Science*. Wiley–VCH, Weinheim 2005; b) Diederich F., Stang P. J. (Eds): *Modern Acetylene Chemistry*. VCH, Weinheim 1995.
2. a) Hintermann L., Labonne A.: *Synthesis* **2007**, 1121; b) Alonso F., Beletskaya I. P., Yus M.: *Chem. Rev.* **2004**, *104*, 3079.
3. Selected recent examples (Au-based catalysts): a) Leyva A., Corma A.: *J. Org. Chem.* **2009**, *74*, 2067; b) Marion N., Ramón R. S., Nolan S. P.: *J. Am. Chem. Soc.* **2009**, *131*, 448; c) Nun P., Ramón R. S., Gaillard S., Nolan S. P.: *J. Organomet. Chem.* **2011**, *696*, 7; d) Carriedo G. A., López S., Suárez-Suárez S., Presa-Soto D., Presa-Soto A.: *Eur. J. Inorg. Chem.* **2011**, 1442.
4. a) Carvalho M. F. N. N., Almeida F. M. T., Galvão A. M., Pombeiro A. J. L.: *J. Organomet. Chem.* **2003**, *679*, 143; b) Carvalho M. F. N. N., Duarte M. T., Herrmann R.: *Collect. Czech. Chem. Commun.* **2006**, *71*, 302; c) Carvalho M. F. N. N., Ferreira A. S. D., Galvão A. M.: *Inorg. Chim. Acta* **2010**, *363*, 1767.
5. a) Carvalho M. F. N. N., Ferreira A. S. D., Herrmann R.: *J. Organomet. Chem.* **2006**, *691*, 4124; b) Carvalho M. F. N. N., Galvão A. M., Ferreira A. S. D.: *J. Organomet. Chem.* **2009**, *694*, 2061.
6. a) Štěpnička P., Císařová I., Sedláček J., Vohlídal J., Polášek M.: *Collect. Czech. Chem. Commun.* **1997**, *62*, 1577; b) Dufková L., Císařová I., Štěpnička P., Kotora M.: *Eur. J. Org. Chem.* **2003**, 2882; c) Dufková L., Matsumura H., Nečas D., Štěpnička P., Uhlík F., Kotora M.: *Collect. Czech. Chem. Commun.* **2004**, *69*, 351.
7. Carvalho M. F. N. N., Costa L. M. G., Pombeiro A. J. L., Schier A., Scherer W., Harbi S. K., Verfürth U., Herrmann R.: *Inorg. Chem.* **1994**, *33*, 6270.
8. Štěpnička P. (Ed.): *Ferrocenes: Ligands, Materials and Biomolecules*. Wiley, Chichester 2008.
9. Perrin D. D., Armarego W. L. F.: *Purification of Laboratory Chemicals*, 3rd ed. Pergamon Press, Oxford 1998.
10. a) Hintermann L., Dang T. T., Labonne A., Kribber T., Xiao L., Naumov P.: *Chem. Eur. J.* **2009**, *15*, 7167; b) Grotjahn D. B., Kragulj E. J., Zeinalipour-Yazdi C. D., Miranda-Soto V., Lev D. A., Cooksy A. L.: *J. Am. Chem. Soc.* **2008**, *130*, 10860.

11. Rosenblum M., Brawn N., Papenmeier J., Applebaum M.: *J. Organomet. Chem.* **1966**, *6*, 173.
12. Doisneau G., Balavoine G., Fillebeen-Khan T.: *J. Organomet. Chem.* **1992**, *425*, 113.
13. Herberhold M., Yan H., Milius W., Wrackmeyer B.: *J. Organomet. Chem.* **2001**, *623*, 149.