Available online at www.sciencedirect.com
SCIENCE DIRECT®
Journal of Organometallic Chemistry 671 (2003) 131–136
Journal of Organometallic Chemistry
www.elsevier.com/locate/jorganchem

Catalytic application of a Ru-alkylidene in the nucleophilic addition of several carboxylic acids on terminal alkynes and the homo-coupling of 1-alkynes

Karen Melis [a], Dirk De Vos [b], Pierre Jacobs [b], Francis Verpoort [a,*]

[a] Division of Organometallic Chemistry and Catalysis, Department of Inorganic and Physical Chemistry, Ghent University, Krijgslaan 281 (S-3), 9000 Ghent, Belgium

[b] Center for Surface Chemistry and Catalysis, Katholieke Universiteit Leuwen, Kasteelpark Arenberg 23, 3001 Heverlee, Belgium

Received 21 January 2003; received in revised form 30 January 2003; accepted 2 February 2003

Abstract

Thermal treatment of Ru-alkylidene (**4**) bearing a triazol-5-ylidene (NHC) ligand (**2**) at 110 °C and addition of a terminal alkyne generates a ruthenium vinylidene. The thermolysed Ru-alkylidene catalyses the vinylation and dimerisation of 1-alkynes. The nucleophilic addition of acetic acid on terminal alkynes proceeds smoothly and regioselective towards the Markovnikov addition. The addition reaction can be tuned by changing the acidity of the carboxylic acid. At increasing acidity, higher conversion of the triple bond is obtained and the vinylation/dimerisation ratio increases. The direct coupling between two 1-alkynes shows a reactivity order, which decreases from 1-octyne > 1,7-octadiyne > phenylacetylene > 3,3 dimethyl-1-butyne. The regioselectivity is strongly dependent on the nature of the terminal alkyne.

Keywords: Ruthenium; Vinylation; Dimerisation; Triazol-5-ylidene

1. Introduction

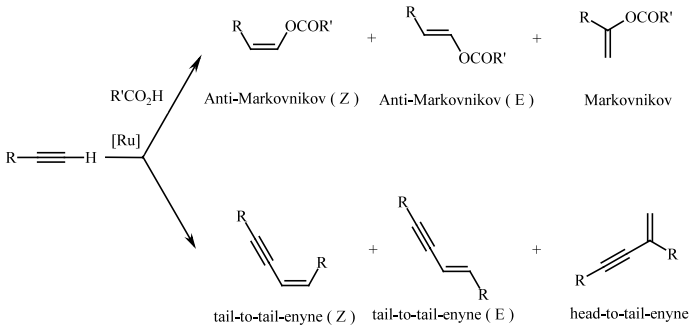
Coordinatively unsaturated ruthenium complexes have proven to be excellent catalysts in a manifold of organic transformations involving C–C and C–H bonds [1,2]. A major advantage of Ru-based complexes is their ability to generate stable metal–vinylidene complexes [3–6]. The metal vinylidenes are formed from the simple addition of a terminal alkyne on a metal complex. Based on the fundamental mechanism, metal vinylidenes are involved in catalytic reactions of the type: dimerisation of alkynes, [2+2] cycloaddition, nucleophilic addition to alkynes and radical cycloaromatisation. Nucleophilic addition of carboxylic acids to terminal alkynes, also known as vinylation, produces enol esters in a regio- and stereo-selective manner (Scheme 1) [7]. Enol esters are useful intermediates for carbon–carbon and carbon–heteroatom bond formation. They have been used for the selective generation of enolates, acylation of carbonyl compounds and *O*- and *N*-acylation under mild conditions. Homo-coupling of 1-alkynes, i.e., dimerisation, represents an easy route to unsaturated dimeric species, in particular 1,3- and 1,4-disubstituted enynes [8]. These are valuable precursors for the synthesis of natural products as well as interesting building blocks for further organic modifications.

N-heterocyclic carbenes having bulky substituents have recently been shown to be suitable ligands to afford highly active catalysts with several transition metals [9]. With regard to ruthenium chemistry the complexes ($Cl_2(PCy_3)(L)Ru{=}CHPh$ with L = imidazol-2-ylidene, triazol-5-ylidene) have evolved to a new generation of very efficient catalytic precursors for the olefin metathesis [10–13].

Recent research in our group revealed that the thermolysed Grubbs' catalyst ($Cl_2(PCy_3)_2Ru{=}CHPh$), which is known as a very good catalyst for the olefin metathesis reactions, generates a ruthenium vinylidene

* Corresponding author. Tel.: +32-9-264-4436; fax: +32-9-264-4983.
E-mail address: francis.verpoort@rug.ac.be (F. Verpoort).

0022-328X/03/$ - see front matter © 2003 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0022-328X(03)00074-3



Scheme 1. Ru-catalysed vinylation and dimerisation of 1-alkynes.

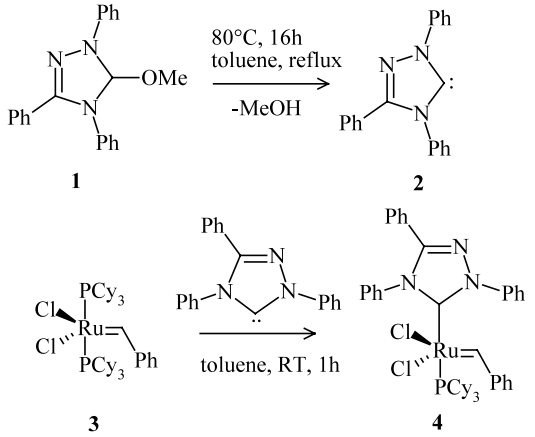
in the presence of a terminal alkyne [14,15]. The thermolysed $Cl_2(PCy_3)_2Ru{=}CHPh$ proved to be an excellent precursor for the transformation of terminal alkynes (Scheme 1).

These results encouraged us to investigate the catalytic properties of $Cl_2(PCy_3)(L)Ru{=}CHPh$ (with L = triazol-5-ylidene) (**4**) with regard to the vinylation and dimerisation of 1-alkynes (Scheme 2).

2. Experimental

2.1. General remarks

All reactions were performed under inert atmosphere using Schlenck techniques. NMR spectra were recorded on a Varian Unity 300 MHz spectrometer. GC–MS analysis were performed on a GC (column SPB™-5 = 30 m × 0.25 mm × 0.25 μm film thickness, carrier gas: He, 100 kPa; detector, FID; gas chromatograph, Varian 4600) and MS (Finnigan MAT ITD). Raman spectra were recorded on a Bruker equinox55/FRA 106. All spectra were recorded with a laser power of 100 mW. The laser (Nd) had a wavelength of 1064 nm. Toluene-d_8 (obtained from Acros) and toluene were dried over Na. $CDCl_3$ (obtained from Acros) was dried over molecular sieves. $Cl_2(PR_3)_2Ru{=}CHPh$ (obtained from Strem Chemicals), 1,3,4-triphenyl-4,5-dihydro-1*H*-1,2,4-triazol-5-ylidene, 1-alkynes, carboxylic acids, cyclooctene (obtained from Acros) were used without further purification. Complex **4** is synthesised as described in Ref. [7].



Scheme 2. Synthesis of $Cl_2(PCy_3)$(triazol-5-ylidene)Ru=CHPh (**4**).

2.1.1. General procedure for the vinylation of 1-alkynes

To a solution of 0.032 mmol of catalyst **4** in toluene (3 ml), are added 2.94 mmol of 1-alkyne and 3.58 mmol of carboxylic acid. The reaction is stirred at 110 °C and followed in situ by ^{1}H-NMR. Yield and selectivity is determined by ^{1}H-NMR, Raman and GC–MS [9].

2.1.2. Dimerisation of 1-alkynes

To a solution of 0.032 mmol of catalyst **4** in toluene (3 ml), is added 3.2 mmol of 1-alkyne. The reaction is stirred at 110 °C and followed in situ by ^{1}H-NMR. Yield and selectivity is determined by ^{1}H-NMR and GC–MS [8].

3. Results and discussion

3.1. Thermal treatment of $Cl_2(PCy_3)$(triazol-5-ylidene)Ru=CHPh (4) and reactivity of 4 with phenylacetylene

The thermal treatment of $Cl_2(PCy_3)$(triazol-5-ylidene)Ru=CHPh (complex **4**) at 110 °C in toluene results in a decomposition of the benzylidene ligand. The thermal decomposition is monitored by ^{1}H- and ^{31}P{H}-NMR and shows the disappearance of the =CHPh ligand, since the doublet at 19.5 and 19.3 ppm (^{1}H-NMR) and the two signals at 24.7 and 25.6 ppm in the ^{31}P{H}-NMR spectrum have disappeared after the treatment at 110 °C. ^{31}P{H}-NMR shows two types of PCy_3 groups ($\delta = 23$ and 28 ppm). No evidence is found for a dissociation equilibrium of a phosphine ligand taking place at the metal center since no free PCy_3 is detected. Isolation and crystallisation of the inorganic compound was unsuccessful, so the nature of the inorganic complex still remains undetermined. The results are analogous to the results obtained with $Cl_2(PCy_3)_2Ru{=}CHPh$ (**3**) [8]. Here also decomposition

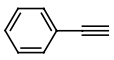
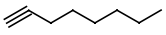
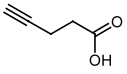
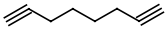
of the carbene ligand is observed and the determination of the inorganic decomposition compound has failed.

A solution of complex **4** in toluene, treated with phenylacetylene is refluxed of toluene for 60 min. A rapid colour change from green to red occurs. $^{31}P\{H\}$-NMR reveal a new type of coordinated PCy_3 ($\delta = 47$ ppm) and some free phosphine. A Ru–vinylidene complex is formed. $^{13}C\{H\}$-NMR determines the C_α and C_β of the Ru–vinylidene at 376.3 and 106.2 ppm, respectively. Analysing the time evolution of NMR spectra of the reaction between complex **4** and a tenfold excess of PhC≡CH provided following evidence: (i) All PhC≡CH is consumed in 1 h to produce PhC≡C–CH=CHPh. (ii) Free PCy_3 is detected by $^{31}P\{H\}$-NMR. (iii) No new phosphorus containing species, next to the signals of complex **4** (24.7 and 25.5 ppm), the thermolysed **4** (23 and 28 ppm) and the Ru–vinylidene (47 ppm), are detected during the transformation from complex **4** to the Ru–vinylidene. (iv) Extra addition of phenylacetylene results in full conversion to PhC≡C–CH=CHPh.

3.2. Vinylation and dimerisation of 1-alkynes catalysed by *4*

After thermal treatment of **4** at 110 °C for 1 h, 96 equivalent of 1-alkyne and 112 equivalent of acetic acid were added and the reaction mixture was stirred for 4 h (Table 1). In the presence of a catalytic amount of complex **4**, the intermolecular addition of acetic acid to

Table 1
Vinylation and dimerisation of terminal alkynes catalysed by ruthenium complex **4**

Run	Alkyne	Acid	Total yield (%)[d]	C-O/C-C bond formation	% M[f]	% AM (c/t)[f]	% head-to-tail[f]	% tail-to-tail[f]
1[a]		CH_3COOH	44.8	53 / 47	67	33 (70/30)	92	8
2[b]		None	32.8	0 / 100	0	0	98	2
3[a]		CH_3COOH	100	100 / 0	0	100 (67/33)	0	0
4[b]		None	25.3	0 / 100	0	0	24	76
5[a]		CH_3COOH	78.3	100 / 0	90	10 (80/20)	0	0
6[b]		None	77.2	0 / 100	[g]	[g]	[g]	[g]
7[c]			98	100 / 0	89	11	0	0
8[d]		CH_3COOH	95.5 Mono:9 % Di : 91%	100 / 0 100 / 0	81 89	19 (78/22) 11 (90/10)	0 0	0 0
9[e]		None	56.2	0 / 100	0	0	60	40

[a]Reactions were carried out by using 3.58 mmol of acetic acid, 2.94 mmol of alkyne and 0.032 mmol of catalyst **4** in toluene (3 ml) under nitrogen. The reaction mixture was stirred at 110 °C for 4 h. [b]Reactions were carried out by using 3.2 mmol of alkyne and 0.032 mmol of catalyst **4** in toluene (3 ml) under nitrogen. The reaction mixture was stirred at 110 °C for 150 min. [c]Reaction was carried out by using 3.2 mmol pentynoic acid and 0.032 mmol of catalyst **4** in toluene (3 ml) under nitrogen. The reaction mixture was stirred at 110 °C for 150 min. [d]Reactions were carried out by using 3.58 mmol of acetic acid, 1.79 mmol of alkyne and 0.032 mmol of catalyst **4** in toluene (3 ml) under nitrogen. The reaction mixture was stirred at 110 °C for 4 h. [e]Reactions were carried out by using 1.6 mmol of alkyne and 0.032 mmol of catalyst **4** in toluene (3 ml) under nitrogen. The reaction mixture was stirred at 110 °C for 150 min. [f]Yield and selectivity as determined with ^{1}H-NMR and GC–MS. [g]The reaction yields oligomers and polymers.

aliphatic alkynes proceeds in quantitative yield (run 3, 5 and 8). Only the transformation of phenylacetylene reaches merely 44.8% and the reaction products consist of 53% of enol esters and 47% of dimeric products (run 1). Also, the intramolecular addition proceeds smoothly (run 7). The vinylation of most terminal alkynes proceeds selectively by the attack on the external C_1 carbon atom of the terminal alkyne and thus production of Markovnikov adducts. The reaction between 3,3-dimethyl-1-butyne and acetic acid exhibits a reversed regioselectivity for addition on the internal C_2 carbon atom of the triple bond (run 3). The formed Anti-Markovnikov adducts mainly consist of the *cis* isomers (67%).

A second catalysed carbon–carbon bond formation reaction is the dimerisation or homo-coupling of 1-alkynes. A solution of **4** (0.032 mmol) in 3 ml toluene was heated at 110 °C. 1-Alkyne (3.2 mmol) was added and the reaction mixture was stirred at 110 °C for 150 min. The activity of catalyst **4** for the dimerisation of the 1-alkynes shows a decreasing order from 1-octyne > 1,7-octadiyne > phenylacetylene > 3,3 dimethyl-1-butyne. The head-to-tail/tail-to-tail ratio is strongly dependent on the nature of the terminal alkyne. The aromatic substituent affords a very good regioselectivity with a head-to-tail/tail-to-tail ratio of 98:2 (run 2). For the di-alkyne, the ratio dramatically decreases to 60:40 (run 9). In the presence of the steric *tert*-butyl group, the selectivity reverses to production of the tail-to-tail adduct as the major adduct (24:76) (run 4). No dimerisation of 1-octyne occurs, although after 4 h 77% of the 1-octyne is consumed (run 6). Investigation of the reaction mixture reveals that the reaction products consist of oligomers and polymers.

The influence of the substituent on the COOH group on the reactivity of catalyst **4** for the vinylation of phenylacetylene is depicted in Fig. 1. The overall yield increases at decreasing pK_a [16]. The intermolecular addition of trichloroacetic acid (p$K_a = 0.66$) on phenylacetylene proceeds smoothly. After 1 h, 91.2% of the phenylacetylene is consumed. The addition of formic acid (p$K_a = 3.75$) reaches a total yield of 77.7% after 4 h of reaction. Acetic and isovaleric acid, which possess a similar acidity (p$K_a = 4.76$ and 4.78, respectively), only reach 44.8 and 47.2% conversion of the triple bond. In the absence of carboxylic acid, 32.8% of the triple bond is converted into the dimeric enyne products. Next to enol esters, the reaction products consist of dimeric products for acetic, formic and isovaleric acid. The vinylation/dimerisation ratio decreases from 60/40 for formic acid, 52/48 for acetic acid and 35/65 for isovaleric acid. Only trichloroacetic acid exclusively yields enol esters.

The preference for the dimerisation of terminal alkynes rises at increasing pK_a and increasing sterical hindrance of the substituent on the COOH group. The

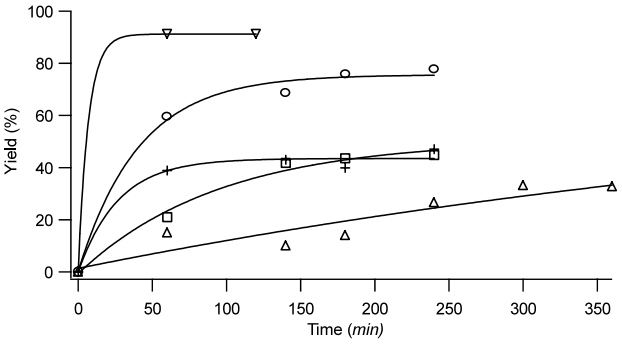


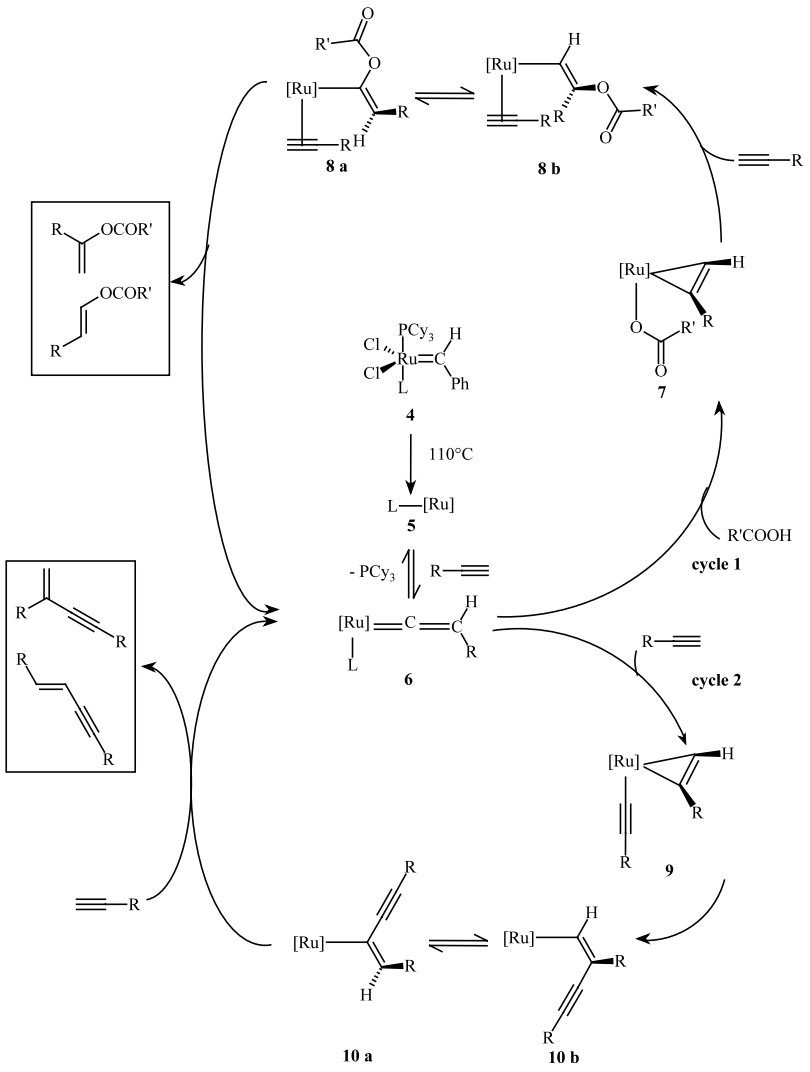
Fig. 1. Influence of nature of carboxylic acid on the nucleophilic addition of the carboxylic acid on phenylacetylene. (△) No acid; (○) formic acid; (□) acetic acid; (+) isovaleric acid; (▽), trichloroacetic acid. Reaction conditions: reactions were carried out by using 3.58 mmol of carboxylic acid, 2.94 mmol of phenylacetylene and 0.032 mmol of catalyst **4** in toluene (3 ml) under nitrogen. The reaction mixture was stirred at 110 °C. The reaction is monitored by Raman spectroscopy by following the diminishing intensity of the C≡C of phenylacetylene using a calibration curve. Selectivity as determined by ^{1}H-NMR.

vinylation occurs preferentially by attack on the internal C_2 carbon atom of the triple bond and thus production of Markovnikov adducts. The intermolecular addition of two 1-alkynes proceeds mainly by addition on the C_2 atom and formation of head-to-tail enynes. Only formic acid shows a regioselectivity for the tail-to-tail addition.

Although detailed mechanism of the catalytic reaction and nature of the inorganic species after thermal treatment of $Cl_2(PCy_3)$(triazol-5-ylidene)Ru=CHPh (**4**) have not been elucidated, the outcome of the thermal treatment of $Cl_2(PCy_3)$(triazol-5-ylidene)Ru=CHPh (**4**) and the reactivity of **4** with phenylacetylene combined with the catalytic performance of **4** suggest some mechanistic insights (Scheme 3). Decoordination of a PCy_3 ligand takes place on the metal center. This creates a vacant site for the, respectively, incoming carboxylic acid (cycle 1) or 1-alkyne (cycle 2).

The nucleophilic addition of the carboxylic acid on the alkyne or vinylation (cycle 1) occurs preferably by the regioselective intermolecular attack of the acid on the internal C_2 carbon atom of the terminal alkyne and thus production of Markovnikov adducts (**8 b**). Generally, Ru-based systems afford enol esters bearing *exo*-olefins. The ring closing of the intramolecular addition proceeds by an attack on the C_2 carbon atom of the triple bond and formation of the Markovnikov 5-*exo* compound (**8 b**). Only the addition of acetic acid on 3,3-dimethyl-1-butyne proceeds by the attack on the external C_1 carbon atom of the terminal alkyne and formation of Anti-Markovnikov adducts (**8 a**).

In the absence of carboxylic acids, only dimerisation (cycle 2) occurs for all terminal alkynes. For arylacetylene derivatives, the intermolecular attack proceeds preferentially on the C_1 of the terminal alkyne (**10 b**).



Scheme 3.

4. Conclusion

Thermal treatment of $Cl_2(PCy_3)$(triazol-5-ylidene)Ru=CHPh (**4**) at 110 °C and subsequent addition of phenylacetylene results in the formation of a Ru–vinylidene complex. The Ru–vinylidene catalyses the nucleophilic addition of carboxylic acids on terminal alkynes or vinylation and the dimerisation of 1-alkynes. The vinylation proceeds in nearly quantitative yield. Addition of the COOH group is preferred on the internal C_2 carbon atom and thus production of Markovnikov adducts. The vinylation is strongly dependent on the pK_a of the added carboxylic acid. At increasing acidity, higher yields and a higher vinylation/dimerisation ratio are obtained. The direct coupling between 1-alkynes or dimerisation is dependent on the nature of the substituent on the triple bond. The best regioselectivity is obtained with the phenyl substituent.

Acknowledgements

K.M. is indebted to the BOF (Bijzonder Onderzoeksfonds) of Ghent University for a research grant. We are indebted to FWO (Fonds voor Wetenschappelijk Onderzoek-Vlaanderen) for a research grant (D.D.V., P.J., F.V.). Financial support by The Research funds of Ghent University is gratefully acknowledged.

References

[1] A. Fürstner, Angew. Chem. Int. Ed. Engl. 39 (2000) 3012 (references herein).
[2] B. Trost, F. Toste, A. Pinkerton, Chem. Rev. 101 (2001) 2067 (references herein).
[3] B. Trost, Chem. Ber. 129 (1996) 1313.
[4] B. Trost, G. Kottirsc, J. Am. Chem. Soc. 112 (1990) 2816.

[5] C. Bruneau, P. Dixneuf, J. Chem. Soc. Chem. Commun. (1997) 507.
[6] C. Bruneau, P. Dixneuf, Acc. Chem. Res. 32 (1999) 311.
[7] (a) E. Rothman, G. Moore, Tetrahedron Lett. 10 (1969) 2553;
(b) H. House, D. Crumrine, A. Teranishi, H. Olmstead, J. Am. Chem. Soc. 95 (1973) 3310;
(c) T. Mitsudo, Y. Hori, Y. Watanabe, J. Org. Chem. 50 (1985) 1566;
(d) C. Ruppin, P. Dixneuf, Tetrahedron Lett. 27 (1986) 6323;
(e) Y. Hori, T. Mitsudo, Y. Watanabe, J. Organomet. Chem. 321 (1987) 397;
(f) Z. Kabouche, C. Bruneau, P. Dixneuf, J. Chem. Soc. Perkin Trans. (1991) 1197;
(g) B. Trost, R. Kulawiec, J. Am. Chem. Soc. 114 (1993) 5579;
(h) P. Dixneuf, C. Bruneau, S. Dérien, Pure Appl. Chem. 70 (1998) 1065;
(i) C. Bruneau, P. Dixneuf, Acc. Chem. Res. 32 (1999) 311;
(j) T. Opstal, F. Verpoort, Synlett 6 (2002) 935.
[8] (a) L. Meriwether, E. Colthup, G. Kennerly, J. Org. Chem. 26 (1961) 5163;
(b) M. Akita, H. Yasuda, A. Nakamura, Bull. Chem. Soc. Jpn. 57 (1984) 480;
(c) A. Echavarren, J. Organomet. Chem. 414 (1991) 393;
(d) C. Bianchini, M. Peruzzini, F. Zanobini, P. Frediani, A. Albinati, J. Am. Chem. Soc. 113 (1991) 5453;
(e) C. Banchini, P. Frediani, D. Masi, M. Peruzzini, F. Zanobini, Organometallics 13 (1994) 4616;
(f) C. Yi, N. Liu, Organometallics 16 (1997) 3910;
(g) C. Yi, N. Liu, Organometallics 17 (1998) 3158;
(h) M. Tenorio, M. Tenorio, M. Puerta, P. Valerga, Organometallics 19 (2000) 1333;
(i) Y. Nishibayashi, M. Yamanashi, I. Wakiji, M. Hidai, Angew. Chem. Int. Ed. Engl. 39 (2000) 2909.
[9] W. Herrman, C. Köcher, Angew. Chem. Int. Ed. Engl. 36 (1997) 2163 (references herein).
[10] L. Ackermann, A. Fürstner, T. Weskamp, F. Kohl, W. Herrmann, Tetrahedron Lett. 40 (1999) 4787.
[11] M. Scholl, T. Trnka, J. Morgan, R. Grubbs, Tetrahedron Lett. 40 (1999) 2247.
[12] D. Enders, K. Breuer, G. Raabe, J. Runsink, H. Teles, J.-P. Melder, K. Ebel, S. Brode, Angew Chem. Int. Ed. Engl. 34 (1995) 1021.
[13] A. Fürstner, L. Ackermann, B. Gabor, R. Goddard, C. Lehmann, R. Mynott, F. Stelzer, O. Thiel, Chem. Eur. J. 7 (2001) 3236.
[14] K. Melis, D. De Vos, P. Jacobs, F. Verpoort, J. Organomet. Chem. 659 (2002) 159.
[15] K. Melis, T. Opstal, F. Verpoort, Eur. J. Org. Chem. 22 (2002) 3779.
[16] A. Martell, R. Smith, Critical Stability Constants, Other Organic Ligands, Plenum Press, New York, 1977, pp. 1–3.