Journal of Organometallic Chemistry, 244 (1983) 401–407
Elsevier Sequoia S.A., Lausanne – Printed in The Netherlands

EVIDENCE FOR *trans*-ACETOXYPALLADATION OF ALKENES IN CHLORIDE-FREE MEDIA

OVE S. ANDELL and JAN-E. BÄCKVALL*

Department of Organic Chemistry, Royal Institute of Technology, S-100 44 Stockholm (Sweden)

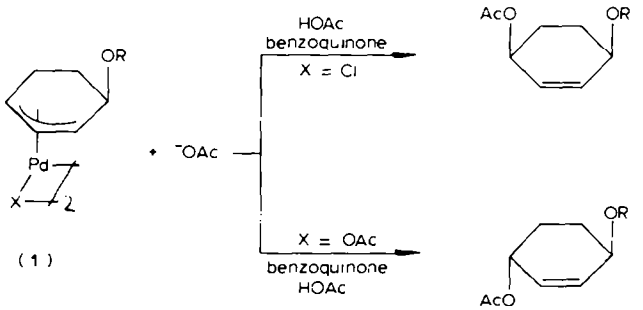
(Received November 2nd, 1982)

Summary

Oxidation of specifically deuterated 3,3-dimethyl-1-butene in chloride-free acetic acid produced deuterated vinyl acetates via an acetoxypalladation-β-elimination sequence. Analysis of the deuterated products by NMR spectroscopy indicates that the oxypalladation occurs *trans*.

Introduction

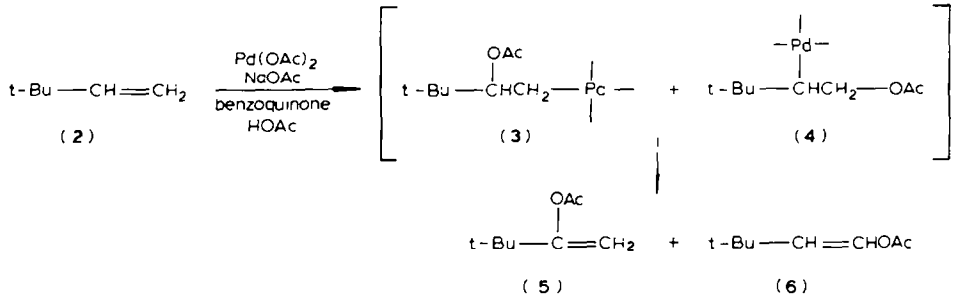
Nucleophilic attack on coordinated alkenes has been studied extensively during the last two decades [1]. In particular the stereochemistry and mechanism of nucleophilic addition to π-olefinpalladium complexes has attracted much attention [2–9]. It is now reasonably clear that oxypalladation, which is an important step in many catalytic reactions [2,7,10], occurs with *trans* stereochemistry. However, it was recently found that nucleophilic addition to π-allylpalladium complexes, which usually follows the same stereochemical pattern as nucleophilic addition to π-olefin complexes [2a], in fact gave *cis*-migration with acetate as nucleophile [11,12]. Thus, acetate attack on π-allylpalladium complex **1**, in chloride-free acetic acid, occurs via a *cis*-migration [12]. In the presence of chloride ligands the usual external attack was observed. A *cis*-acetoxypalladation of a pinene derivative has also recently been reported [13].



0022-328X/83/0000–0000/$03.00

Since most stereochemical studies of oxypalladations were carried out in chloride ion containing media, we decided to study the stereochemistry of acetoxypalladation in chloride-free acetic acid. Our aim was to find out whether a *cis*-migration similar to that occurring in π-allylpalladium complexes can occur in the nucleophilic addition of acetate to π-olefinpalladium complexes. Our results show that *trans*-acetoxypalladation is the favoured pathway even under conditions which gave *cis*-migration in π-allylpalladium systems.

It has been reported [14] that palladium-catalyzed oxidation of 3,3-dimethyl-1-butene **2** produces a mixture of the regioisomeric vinyl acetates **5** and **6**. This reaction proceeds via oxypalladation adducts **3** and **4**, which on β-elimination give **5** and **6**. A remarkable influence of the acetate concentration on the ratio of **5**/**6** was observed. Thus, in the absence, or at low concentrations of sodium acetate, **5** predominates. With increased acetate concentration the relative amount of **6** increases and at 1 *M* NaOAc the ratio **5**/**6** is 1/2.

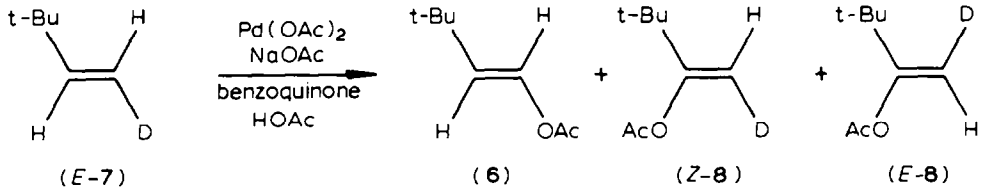


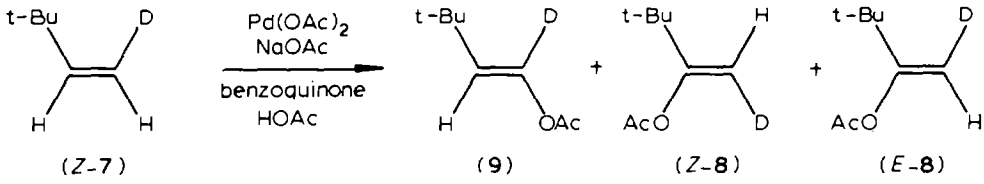
Since we had observed [12] a similar dependence of the stereochemistry of acetate attack on π-allylpalladium complexes on acetate concentration, we decided to study whether **5** and **6** are formed via stereochemically different pathways.

Results and discussion

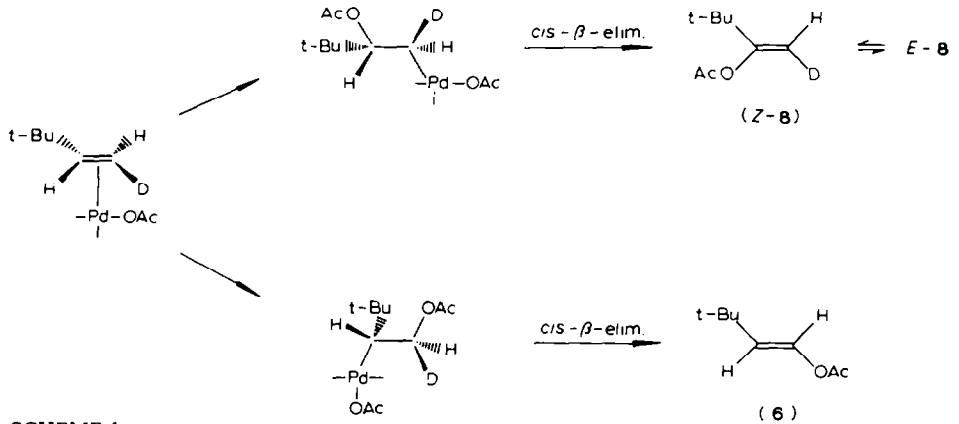
The specifically deuterated olefins *E*- and *Z*-1-deuterio-3,3-dimethyl-1-butene, readily available from the appropriate acetylene via a hydroalumination [15]-hydrolysis (D_2O or H_2O) sequence (see Experimental) were used in this investigation. Since the β-hydride elimination in the putative oxypalladation intermediates (cf. **3** and **4**) is stereospecific and occurs *cis* [4,8,16], analysis of the deuterated vinylic acetates formed provides information about the stereochemistry of the oxypalladation step. Oxidation of *E* and *Z*-**7** according to the procedure described by Henry [14], using 0.4 *M* NaOAc, gave a mixture of deuterated vinylic acetates (Scheme 1). The reaction is very slow [14] and was usually allowed to proceed for a period of 24 h. In most of the experiments the olefin was used in a five-fold excess over benzoquinone. The product mixture was analyzed by ^{1}H NMR spectroscopy and the results from some experiments are given in Table 1. Analysis of the product from oxidation of *E*-**7** for 24 h (entry 2) showed that the terminal vinylic acetate is ~ 76% undeuterated **6**. The other regioisomer **8** was found to be a *Z*/*E* mixture in a ratio of 2.8/1. Similarly, *Z*-**7** was oxidized to give **9**, now with the deuterium intact (~ 91% deuterated), and *Z*-**8**/*E*-**8** in a ratio of 1/2.8.

The formation of **6** from *E*-**7** and **9** from *Z*-**7** is consistent with a *trans*-acetoxypal-





ladation followed by a *cis*-β-hydride elimination (Scheme 1). Analogously, the expected regioisomeric acetate from a *trans*-acetoxypalladation *cis*-β-elimination sequence is *Z*-**8** from *E*-**7** and *E*-**8** from *Z*-**7**. These were indeed found to be the major isomers in each case.



SCHEME 1

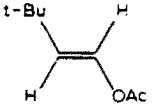
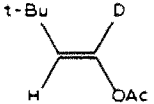
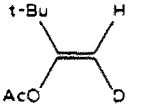
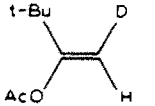
In order to find out whether isomerization of the olefin could account for some loss of stereospecificity, the unreacted olefin was analyzed at the end of the reaction period. Analysis by ^{1}H NMR spectroscopy showed that no detectable isomerization occurred when the olefin was used in a five-fold excess and the reaction time was not longer than 24 h. With longer reaction times (entry 1) or less olefin (entry 4) some isomerization of the olefin was observed.

It is likely that the loss of stereospecificity in the formation of **8** is a result of an isomerization *E*-**8** $\rightleftarrows$ *Z*-**8** via vinylic ester exchange. Such exchange reactions are well known [17], and proceed via an acetoxypalladation-deacetoxypalladation sequence leading to *E*-*Z* isomerization. We found that the ratio *Z*-**8**/*E*-**8** changes with the reaction time (Table 1), which is consistent with a secondary isomerization. Thus, oxidation of *Z*-**7** for 8 h gave a ratio *Z*-**8**/*E*-**8** of 1/3.5. In another experiment *E*-**7** was oxidized over a 48 h period to give *Z*-**8** and *E*-**8** in a ratio of 2.5/1.

The formation of **6** and **9** via elimination of palladium deuteride or hydride

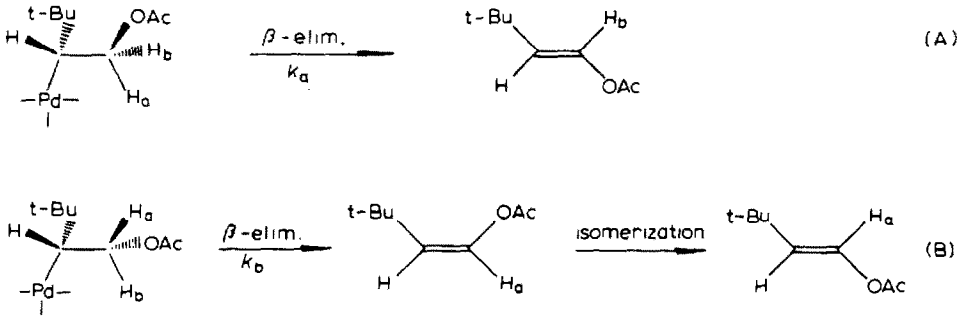
TABLE 1

PALLADIUM-CATALYZED OXIDATION OF *E*-7 AND *Z*-7 IN ACETIC ACID [a]

Entry	Starting olefin	Ratio olefin/ benzoquinone	Reaction time (h)	 (6)	 (9)	6/9	 (*Z*-8)	 (*E*-8)	*Z*-8/*E*-8	Recovered olefin *E*-7 (%)	Recovered olefin *Z*-7 (%)
1	*E*-7	5	48			2.3/1			2.5/1	92	8
2	*E*-7	5	24			3.1/1			2.8/1	> 98	0
3	*E*-7	5	8			[b]/[b]			3.2/1	> 98	0
4	*E*-7	2	24			2.0/1			2.1/1	90	10
5	*Z*-7	5	24			1/10			1/2.8	0	> 98
6	*Z*-7	5	8			1/10			1/3.5	– [c]	– [c]
7	*Z*-7	1	168			1/11			1/1.4	– [c]	– [c]

[a] All reactions were performed at room temperature using a ratio $Pd(OAc)_2$/benzoquinone of 0.27/1. [b] Could not be determined accurately because of the low yield. [c] Not determined.

respectively from an intermediate σ-alkylpalladium complex deserves some comment. Elimination via a conformation A in which the t-butyl and acetate groups are *trans* to one another is greatly favoured. This elimination gives the *E*-product (Scheme 2). However, a less favoured elimination via conformation B, in which the



SCHEME 2

t-butyl and acetate groups are *cis* to one another, can also occur. The latter reaction eliminates the other diastereotopic proton and gives the *Z*-product which will isomerize [17] to the *E*-product under the reaction conditions (Scheme 2).

It is conceivable that product **9** from the oxidation of *E*-**7** (H_a = D) and product **6** from the oxidation of *Z*-**7** (H_b = D) are formed via the less favoured elimination (B). Thus, entries 2 and 5 indicate that there is a deuterium isotope effect of 1.8 in the β-elimination and that the ratio of the rates between the eliminations A and B, k_a/k_b is approximately 5.6/1.

The relative ratio of **6** to **9** in the oxidation of *E*-**7** is sensitive to isomerization of the olefin, since the isomerized olefin (*Z*-**7**) reacts much faster than *E*-**7** and gives essentially only **9**. Therefore even a slight olefin isomerization decreased the selectivity for formation of **6** from *E*-**7** (entries 1 and 4). A rate ratio of approximately 2 for the oxidation of *Z*-**7** and *E*-**7** to terminal acetate would account for the decreased selectivity in entries 1 and 4.

Thus, the results show that nucleophilic attack by acetate on π-olefin-palladium complexes occurs with *trans* stereochemistry even under conditions in which *cis*-attack on π-allylpalladium complexes occurs. However, our results do not allow us to exclude completely a minor pathway via a *cis*-addition. For example if the rate ratio, k_a/k_b between the eliminations in Scheme 2 is > 5.6, one would have to assume some *cis*-addition to account for the results. Still the *trans*-addition would have to be $> 85\%$. The observation by Henry that 1-(trideuterioacetoxy)cyclopentene does not exchange with acetic acid when $PdCl_2$ is used as catalyst [18] but does exchange with acetic acid when $Pd(OAc)_2$ is used as catalyst [19] in the vinylic ester exchange reaction [17], suggests that some *cis*-acetoxypalladation occurs in the latter case. Thus, in changing from a chloride to an acetate system the acetoxypalladation goes from a very stereospecific *trans*-addition to a less stereospecific addition [20]. However, the present results show that even in a chloride free acetate system the *trans*-addition to olefins is greatly favoured over *cis*-addition.

We have recently suggested [1a] that *trans* nucleophilic addition to π-olefin-palladium complexes is mainly a charge controlled process and that *cis* nucleophilic addition (via migration) is frontier controlled [21]. The frontier controlled *cis*-migra-

tion reaction would therefore be favoured for nucleophiles with a high energy HOMO (highest occupied molecular orbital) such as hydride and methyl anion, whereas nucleophiles with a low lying HOMO would be very unwilling to migrate. Oxygen and nitrogen nucleophiles, which are hard bases, have low-lying HOMOs [21] and a *cis*-migration would be very disfavoured for these nucleophiles. Accordingly they are known to add with *trans* stereochemistry [2–6]. The results in the present paper give further support for this theory, and show that a *cis*-migration of an oxygen nucleophile from palladium to a coordinated olefin is an unfavourable process.

Experimental

NMR spectra were recorded at 200 MHz on a Bruker WP 200 FT Spectrometer. Benzoquinone was recrystallized from ligroine. Toluene was dried over $CaCl_2$. Diisobutylaluminum hydride (DIBALH) in toluene (1.2 *M*) was purchased from FLUKA AG. D_2O (99.7% deuterium) was obtained from Merck Sharp and Dohme. All reactions were performed under a dry nitrogen atmosphere.

E-1-deuterio-3,3-dimethyl-1-butene (E-7)

To a stirred solution of 3,3-dimethyl-1-butyne (12.5 ml, 8.4 g, 102 mmol) in toluene (25 ml) at 45°C was added 93 ml of a solution of diisobutyl aluminum hydride (112 mmol) in toluene during 2.5 h. After the addition was complete the temperature was increased to 55°C and the stirring continued for another 2 h. The clear solution was cooled to room temperature and D_2O (25 ml) was added during 3 h with vigorous stirring. The slurry thus formed (aluminum hydroxide) was stirred at 25°C for 4 days until the aluminum hydroxide had become more crystalline and easier to handle. The aluminum hydroxide was filtered off and the product (*E*-**7**) was distilled from the toluene phase through a column (10 × 1.5 cm) packed with small glass coils (5 × 2 mm), b.p. 42°C (1 atm). Yield: 5.3 g (61%). NMR ($CDCl_3$): δ 1.02 (s, 9, $(CH_3)_3C$), 4.90 (d *J* 17.6 Hz, 1, CHD), 5.86 (d with deuterium splitting, 1, CH).

1-Deuterio-3,3-dimethyl-1-butyne

3,3-Dimethyl-1-butyne (9.1 g, 13.5 ml, 110 mmol) was stirred with 40 ml of a 0.5 *M* NaOD solution in D_2O for 20 h, at 25°C. The product was separated from the aqueous phase in a separating funnel and dried ($MgSO_4$).

Z-1-Deuterio-3,3-dimethyl-1-butene (Z-7) was prepared by hydroalumination of 1-deuterio-3,3-dimethyl-1-butyne followed by H_2O quenching according to the procedure described above. NMR ($CDCl_3$) δ 1.02 (s, 9, Me_3C), 4.82 (d *J* 10.6 Hz, 1, CHD), 5.85 (d with deuterium splitting, 1, CH).

Oxidation of E-7 and E-8

Following the procedure used by Henry [14], palladium acetate (125 mg, 0.556 mmol) and sodium acetate (660 mg, 8 mmol) was dissolved in acetic acid (20 ml) at 60°C during 1 h and then the mixture was stirred at 25°C for 6 h. Benzoquinone (215 mg, 2 mmol) was dissolved in the solution followed by the appropriate olefin **7** (0.85 g, 10 mmol). The solution was stirred at room temperature for 24 h, then a cold finger with a small container on its tip was introduced into the flask. After 1 h

the small container was full of an acetic acid solution of unreacted olefin. This olefin was analyzed by NMR spectroscopy and found to have the same isomeric purity as the starting olefin.

After the sample of olefin had been taken, water (10 ml) and brine (20 ml) were added to the reaction mixture. The resulting mixture was extracted with pentane (7 × 15 ml). The combined pentane phases were washed with water (2 × 10 ml), 10% Na_2CO_3 (2 × 10 ml) water (10 ml) and brine (10 ml). The organic phase was dried ($MgSO_4$) and pentane was distilled off at atmospheric pressure using a vigreux column. The residue was dissolved in $CDCl_3$ and analyzed by ^1H NMR spectroscopy. ^1H NMR ($CDCl_3$) *Z*-**8**: δ 4.63 ppm (s, 1, =C*H*D); *E*-**8**: δ 4.85 ppm (s, 1, =CHD); **9**: δ, 5.47 ppm (t, *J*(HD) 1.8 Hz, 1, t-BuC*H*=).

The ^1H NMR spectra for the undeuterated parent compounds **5** and **6** [14] are given for completeness. ^1H NMR ($CDCl_3$) **5**: δ (ppm) 1.10 (s, 9, t-Bu), 2.17 (s, 3, CH_3CO) 4.64 (d, *J*(HH) 2 Hz, 1, one of $=CH_2$), 4.88 (d, 1, one of $=CH_2$); **6** ^1H NMR ($CDCl_3$): δ (ppm) 1.06 (s, 9, t-Bu), 2.11 (s, 3, CH_3CO) 5.48 (d, *J* 12.6 Hz, 1, t-BuCH=), 7.06 (d, 1, =*CH*OAc).

Acknowledgement

We are greatful for financial support from the Swedish Natural Science Research Council.

References

1 (a) J.E. Bäckvall in P.S. Braterman (Ed.), Reaction of Coordinated Ligands, Plenum Press, in press; (b) S.G. Davies, M.L.H. Green and D.M.P. Mingos, Tetrahedron, 34 (1978) 3047.
2 (a) J.E. Bäckvall, B. Åkermark and S.O. Ljunggren, J. Am. Chem. Soc., 101 (1979) 2411; (b) J.K. Stille and R. Divakaruni, J. Organometal. Chem., 169 (1979) 239.
3 (a) D.E. James, L.F. Hines and J.K. Stille, J. Am. Chem. Soc., 98 (1976) 1806; (b) H. Kurosawa, T. Majima and N. Asada, J. Am. Chem. Soc., 102 (1980) 6996.
4 P.M. Henry and G.A. Ward, J. Am. Chem. Soc., 93 (1971) 1494.
5 (a) B. Åkermark, J.E. Bäckvall, K. Siirala-Hansen, K. Sjöberg and K. Zetterberg, Tetrahedron Lett., (1974) 1363; (b) B. Åkermark and J.E. Bäckvall, Tetrahedron Lett., (1974) 1363.
6 H. Kurosawa and N. Asada, Tetrahedron Lett., (1979) 255.
7 (a) P.M. Henry, Adv. Organometal Chem., 13 (1975) 363; (b) F.J. McQuillin, Tetrahedron, 30 (1974) 1661.
8 (a) S.I. Marahashi, M. Yamamura and N. Mita, J. Org. Chem., 42 (1977) 2870; (b) P.M. Henry and G.A. Ward, J. Am. Chem. Soc., 94 (1972) 673.
9 N. Gragor and P.M. Henry, J. Am. Chem. Soc., 103 (1981) 681.
10 (a) J. Smidt, W. Hafner, R. Jira, J. Sedlmeier, R. Sieber, R. Rüttinger and H. Kojer, Angew. Chem., 71 (1959) 176; (b) J. Smidt, W. Hafner, R. Jira, R. Sieber, J. Sedlmeier and A. Sabel, Angew. Chem., 74 (1962) 93.
11 J.E. Bäckvall, R.E. Nordberg, E.E. Björkman and C. Moberg, J.Chem. Soc. Chem. Commun., (1980) 943.
12 J.E. Bäckvall and R.E. Nordberg, J. Am. Chem. Soc., 103 (1981) 4959.
13 T. Hosokawa, Y. Imada and S.I. Murahashi, Tetrahedron Lett., 23 (1982) 3373.
14 S. Winstein, J. McCaskie, H.B. Lee and P.M. Henry, J. Am. Chem. Soc., 98 (1976) 6913.
15 (a) G. Wilke and H. Müller, Liebigs Ann. Chem., 618 (1958) 267; (b) D.W. Patrick, L.K. Truesdale, S.A. Biller and K.B. Sharpless, J. Org. Chem., 43 (1978) 2628.
16 T. Majima and H. Kurosawa, J. Chem. Soc. Chem. Commun., (1977) 610.
17 P.M. Henry, Acc. Chem. Res., 6 (1973) 16.
18 P.M. Henry, J. Am. Chem. Soc., 93 (1971) 3853.
19 R.N. Pandey and P.M. Henry, Can. J. Chem., 53 (1975) 2223.
20 P.M. Henry, Palladium Catalyzed Oxidation of Hydrocarbons, D. Reidel Publishing Company, Dordrecht, Holland, 1980, pp. 90 and 123.
21 G. Klopman, J. Am. Chem. Soc., 90 (1968) 223.