Palladium(II)-Catalyzed Exchange and Isomerization Reactions

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In the last dozen years considerable advances have been made in homogeneous catalysis in general and in Pd(II) catalysis in particular. No doubt much of the impetus in Pd(II) catalysis research was provided by disclosure of the Wacker process for manufacture of acetaldehyde by Smidt and coworkers in 1959[1] (eq 1). This process is now the preferred method of man-

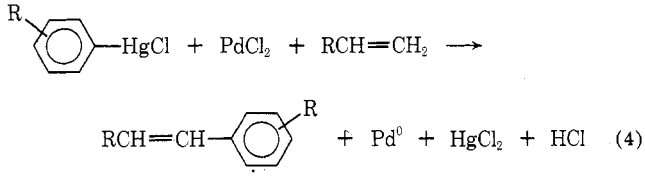
$$C_2H_4 + \tfrac{1}{2}O_2 \xrightarrow[CuCl_2,\ H_2O]{PdCl_2} CH_3CHO \quad (1)$$

ufacturing acetaldehyde. Also, ketones can be produced by oxidation of higher olefins (eq 2).

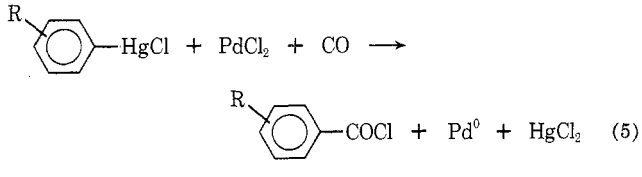
$$RCH{=}CHR' + \tfrac{1}{2}O_2 \longrightarrow RCOCH_2R' \quad (2)$$

This concentrated effort on Pd(II) catalysis has resulted in discovery of a number of new reactions. One which has commercial possibilities is the vinyl ester synthesis[2] (eq 3). Closely related is the olefin arylation reaction[3] (eq 4).

$$C_2H_4 + 2OAc^- \xrightarrow[O_2]{Pd(II)} CH_2{=}CHOAc + HOAc \quad (3)$$



Carbon monoxide is involved in many of the new reactions such as the aromatic acid synthesis[4] (eq 5)

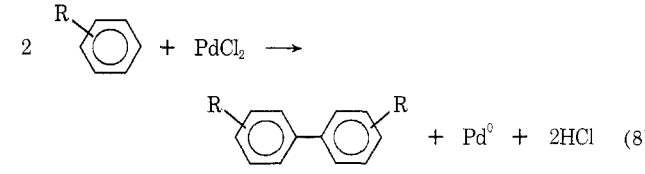


and the isocyanate synthesis[5] (eq 6). In some cases

$$RNH_2 + PdCl_2 + CO \rightarrow RNCO + 2HCl + Pd^0 \quad (6)$$

both olefin and CO are involved, as in the carbonylation of olefins[6] (eq 7). A reaction which involves neither olefin nor CO is the aromatic coupling reaction[7] (eq 8).

$$RCH{=}CH_2 + CO + PdCl_2 \rightarrow RCHClCH_2COCl + Pd^0 \quad (7)$$



The examples given above are only a few of the many new Pd(II)-catalyzed reactions.[8]

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In spite of these synthetic advances in Pd(II) chemistry, relatively little effort has been expended on the mechanisms of Pd(II) catalysis. In fact, the only reaction which has been extensively studied is the basic reaction of the Wacker process (eq 9). The

$$PdCl_4^{2-} + C_2H_4 + H_2O \rightarrow Pd^0 + CH_3CHO + 2HCl + 2Cl^- \quad (9)$$

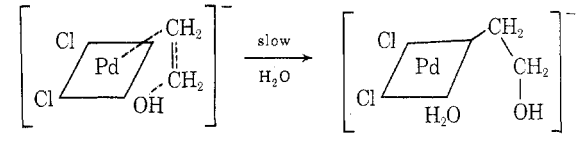
results of several kinetic studies[9-11] of this reaction are summarized in eq 10. It is generally agreed that

$$-d[C_2H_4]/dt = k[PdCl_4^{2-}][C_2H_4]/([H^+][Cl^-]^2) \quad (10)$$

the mechanism for this reaction is that given by eq 11-14. The important feature of this mechanism is

$$PdCl_4^{2-} + C_2H_4 \overset{K_1}{\rightleftharpoons} PdCl_3(C_2H_4)^- + Cl^- \quad (11)$$

$$PdCl_3(C_2H_4)^- + H_2O \overset{K_2}{\rightleftharpoons} PdCl_2(OH)(C_2H_4)^- + HCl \quad (12)$$



$$Cl_2(H_2O)Pd{-}CH_2CH_2OH \xrightarrow{fast} Pd^0 + CH_3CHO + HCl + Cl^- + H_2O \quad (14)$$

the cis insertion of the elements of Pd(II) and coordinated OH across the olefinic double bond (eq 13) to give the β-hydroxyethylpalladium(II) alkyl (or

(1) J. Smidt, R. Jira, J. Sedlmeier, R. Sieber, R. Rüttinger, and H. Kojer, *Angew. Chem., Int. Ed. Engl.*, 1, 80 (1962).
(2) I. I. Moiseev, M. N. Vargaftik, and Ya. K. Sirkin, *Dokl. Akad. Nauk SSSR*, 133, 377 (1960).
(3) R. F. Heck, *J. Amer. Chem. Soc.*, 90, 5518 (1968), and following papers.
(4) P. M. Henry, *Tetrahedron Lett.*, 2285 (1968).
(5) E. W. Stern and M. L. Spector, *J. Org. Chem.*, 31, 596 (1966).
(6) J. Tsuji, M. Morikawa, and J. Kiji, *J. Amer. Chem. Soc.*, 86, 8451 (1964).
(7) R. van Helden and C. Verberg, *Recl. Trav. Chim. Pays-Bas*, 84, 1263 (1965).
(8) For recent reviews see: (a) E. W. Stern, *Catal. Rev.*, 1, 74 (1968); (b) J. Tsuji, *Accounts Chem. Res.*, 2, 144 (1969); (c) F. R. Hartley, *Chem. Rev.*, 69, 799 (1969); (d) P. M. Henry, *Trans. N. Y. Acad. Sci.*, 33, 41 (1971); (e) P. M. Maitlis, "Organic Chemistry of Palladium," Vol. II, Academic Press, New York, N. Y., 1971.
(9) I. I. Moiseev, M. N. Vargaftik, and Ya. K. Sirkin, *Dokl. Akad. Nauk SSSR*, 153, 140 (1963).
(10) R. Jira, J. Sedlmeier, and J. Smidt, *Justus Liebigs Ann. Chem.*, 693, 99 (1966).
(11) P. M. Henry, *J. Amer. Chem. Soc.*, 86, 3246 (1964); 88, 1595 (1966).

hydroxypalladation adduct, in analogy to the well-known hydroxymercuration adducts[12]). The kinetic expression (eq 10) is consistent with the need for both coordinated ethylene and OH since it contains the $[H^+]$ and $[Cl^-]^2$ terms in the numerator of the rate expression required by eq 11 and 12.[13]

The only other system which has been studied to any extent is the oxidation of olefins to enol and allylic acetates in acetic acid (AcOH). The initial product distributions for several straight-chain olefins indicated that the reaction proceeds *via* an acetoxypalladation route[14] analogous to that proposed for the Wacker reaction. With ethylene the reaction scheme would be as given by eq 15. Because of the

$$C_2H_4 + Pd(OAc)_2 \rightarrow AcOPdCH_2CH_2OAc \rightarrow HPdOAc + CH_2{=}CHOAc \quad (15)$$

complexities of the system, an interesting kinetic study[15] was unable definitely to determine if the acetoxypalladation proceeds *via* coordinated acetate addition to coordinated olefin in a fashion similiar to that postulated for hydroxypalladation (eq 13).

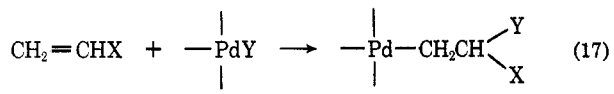
No doubt experimental difficulties are one reason Pd(II) catalysis has not been studied more thoroughly. The rates are often inconveniently slow and, since most are oxidative in nature, they are complicated by the effects of precipitation of Pd metal.

One type of Pd(II)-catalyzed reactions free of these complications comprises the vinylic and allylic exchange reactions represented by eq 16 (X or Y =

$$CH_2{=}CHX \text{ or } CH_2{=}CHCH_2X + Y^- \overset{Pd(II)}{\rightleftharpoons} CH_2{=}CHY \text{ or } CH_2{=}CHCH_2Y + X^- \quad (16)$$

OOCR, Cl, OR, NR_2 etc.). Since this reaction is nonoxidative in nature, these reactions do not precipitate Pd metal, and the rates are in a convenient range for measurement at 25°. Moreover, stereochemical evidence for mechanism can readily be obtained in these systems. Therefore the author chose this type of reaction for studies aimed at elucidating the detailed paths of Pd(II) catalysis.

By analogy with the Wacker reaction, these reactions might be expected to proceed by addition of the Pd(II) and Y followed by elimination of Pd(II) and X, as shown in eq 17 and 18. One point on



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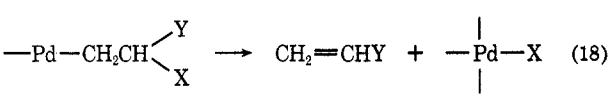


(18)

which these studies would hopefully shed light is whether or not coordination of Y to Pd(II) is cequired for insertion across the olefinic double bond. Other questions which these studies would attempt to answer concern the stereochemistry of attack of various nucleophiles, Y, the need for coordination of organic substrates, and the role of coordination unsaturation. These questions are not only important to Pd(II) catalysis but are basic to homogeneous catalysis in general.[16]

All kinetic studies reported in this Account were carried out in acetic acid, and most involved palladium(II) chloride salts in LiCl-containing solutions. In order properly to interpret the kinetics, it is necessary to know the equilibria between Pd(II) and other species in solution. A molecular weight and spectral study[17] indicated the equilibria represented by eq 19 and 20 to be operative. K_3 has a value of 0.1 M^{-1}

$$Li_2Pd_2Cl_6 + 2LiCl \overset{K_3}{\rightleftharpoons} 2Li_2PdCl_4 \quad (19)$$

$$2LiCl \overset{K_D}{\rightleftharpoons} Li_2Cl_2 \quad (20)$$

and K_D is 2.6 M^{-1} at 25°. No complexing of LiOAc by Pd(II) could be detected in the chloride containing systems.

Vinyl Ester Exchange with Acetic Acid

The vinyl ester exchange reaction (eq 21), was first

$$CH_2{=}CHOOCR + HOAc \overset{Pd(II)}{\rightleftharpoons} CH_2{=}CHOAc + HOOCR \quad (21)$$

reported by Smidt and coworkers.[1] Their subsequent study of the mechanism indicated that the reaction proceeds by the route represented by eq 17 and 18.[18] The kinetics of the reaction was determined using either deuterated vinyl acetate[19] (R = CD_3) or vinyl propionate[20] (R = C_2H_5) as labels. Over a wide range of LiOAc and LiCl concentrations the rate expression is given by eq 22. The k_1' and k'' must cor-

$$\text{rate} = ([Li_2Pd_2Cl_6][\text{vinyl ester}]/[LiCl]) \times (k_1' + k_1''[LiOAc]) \quad (22)$$

respond to reaction with acetic acid solvent and acetate ion, respectively. Their relative values are such that at [LiOAc] = 0.1 M the k_1' path contributes only 10% of the total rate.

Two features of the kinetics deserve comment. First, the reaction is first order in dimer. If the first step of the reaction is formation of a Pd(II)–olefin π complex, as usually assumed for Pd(II)-catalyzed reactions, then the complex formation must be occurring *via* eq 23 rather than eq 24.[21]

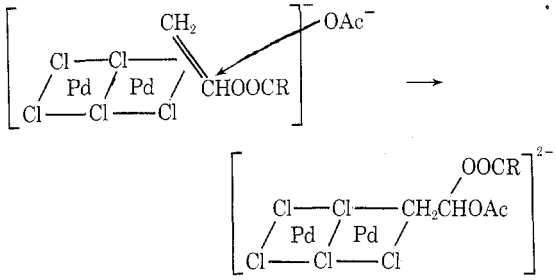
$$Li_2Pd_2Cl_6 + C_2H_3OOCR \overset{K_4}{\rightleftharpoons} Li_2Pd_2Cl_5(C_2H_3OOCR) + LiCl \quad (23)$$

$$Li_2Pd_2Cl_6 + 2C_2H_3OOCR \overset{K_5}{\rightleftharpoons} 2LiPdCl_3(C_2H_3OOCR) \quad (24)$$

Second, the LiCl inhibition appears only to the first power. If coordination of both olefin and acetate were required, an $[LiCl]^2$ inhibition term would be expected in the rate expression. This result strongly

(12) J. Chatt, *Chem. Rev.*, 48, 7 (1951).
(13) It should be pointed out that the kinetics do not absolutely require cis attack of Pd-OH. See P. M. Henry, *Advan. Chem. Ser.*, **No. 70**, 136 (1968).
(14) W. Kitching, Z. Rappoport, S. Winstein, and W. G. Young, *J. Amer. Chem. Soc.*, 88, 2054 (1966).
(15) I. I. Moiseev, M. N. Vargaftik, S. V. Pestrikov, O. G. Levanda, T. N. Romanova, and Ya. K. Sirkin, *Dokl. Akad. Nauk SSSR*, **171**, 1365 (1969).
(16) J. P. Collman, *Accounts Chem. Res.* **1**, 136 (1968).
(17) P. M. Henry and O. W. Marks, *Inorg. Chem.*, **10**, 373 (1971).
(18) A. Sabel, J. Smidt, R. Jira, and H. Prigge, *Chem. Ber.*, **102**, 2939 (1969).
(19) P. M. Henry, *J. Amer. Chem. Soc.*, **93**, 3853 (1971).
(20) P. M. Henry, *J. Amer. Chem. Soc.*, **94**, 7316 (1972).
(21) Equation 16 would require a [vinyl ester]$^{1/2}$ term in the rate expression (eq 14).

suggests that acetate is attacking from outside the coordination sphere of Pd(II). This type of addition



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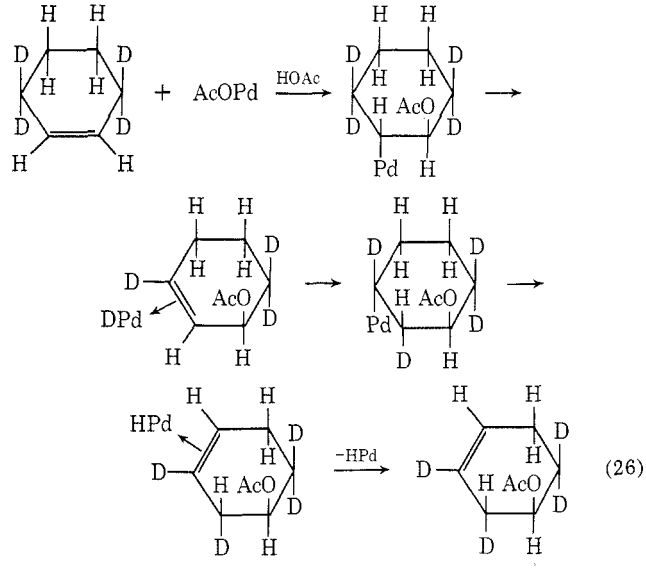
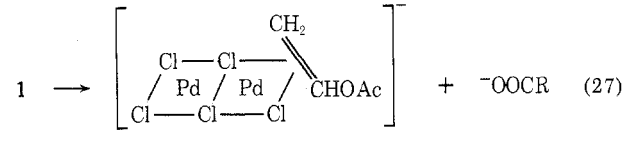
suggest trans stereochemistry, and indeed the products of oxidation of tetradeuteriocyclohexene are best explained by trans acetoxypalladation and cis palladium(II) hydride elimination.[22] The reaction scheme for formation of 3-cyclohexen-1-yl acetate is shown in eq 26.



(26)

The most reasonable reaction sequence consistent with the rate expression is thus formation of a dimeric π complex *via* eq 23, followed by trans attack of acetate or acetic acid to give an acetoxypalladation adduct *via* eq 25. Reversal of eq 25 with ejection of $^{-}$OOCR instead of acetate completes exchange (eq 27).



(27)

To test this mechanism, the stereochemistry of the OAc_D exchange of *cis*- and *trans* 1-propen-1-yl acetate and propionate were determined. Exchange occurred only with isomerization.[19] As shown in eq 28 this result is consistent with the acetoxypalladation mechanism in which acetoxypalladation is stereospecific (A = addition, E = elimination). It is inconsistent with S_N2 attack of acetate on the carbon–oxygen bond, a mechanism which has been suggested for some Pd(II)-catalyzed oxidations, and which would predict retention of configuration.

(22) P. M. Henry and G. A. Ward, *J. Amer. Chem. Soc.*, 93, 1494 (1971).

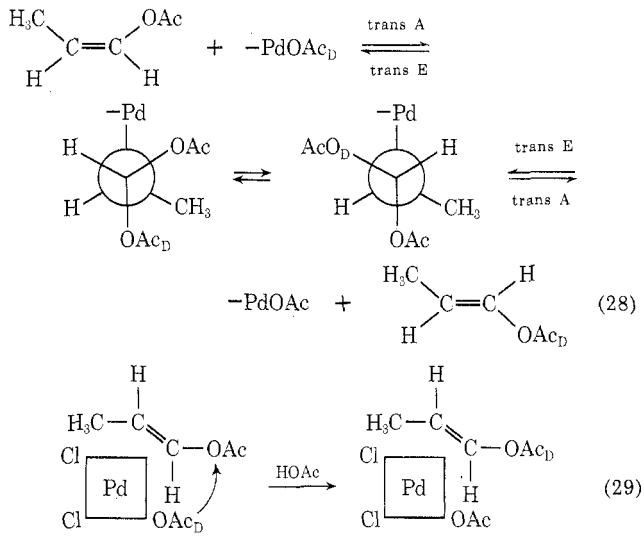


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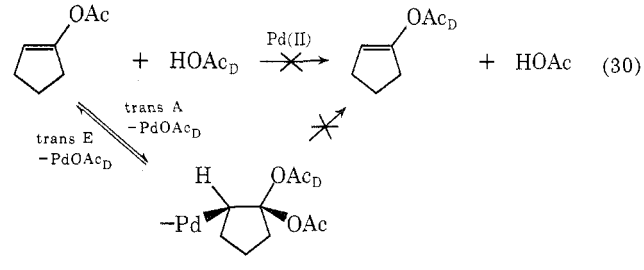
Table I lists the rates of exchange of several enol acetates.[19] Substitution on vinylic carbon strongly inhibits exchange. This result is consistent with the acetoxypalladation mechanism since addition of the elements of acetate and Pd(II) dimer across a double bond would have a large steric requirement.

Table I
Rates of Exchange of Various Enol Acetates at 25°

Enol acetate	k, M^{-1} sec^{-1}
CH_2=CHOAc	2.0×10^{-2}
trans-CH_3CH=CHOAc	5.0×10^{-4}
cis-CH_3CH=$C(CH_3)$OAc	3.2×10^{-8}
1-Cyclopentenyl acetate	$<10^{-9}$

It is surprising at first glance that 1-acetoxy-1-cyclopentene does not exchange detectably since, on steric grounds, it would be expected to have approximately the same rate as 2-acetoxy-2-butene. However, as shown by eq 30, stereochemically pure acetoxypalladation (and deacetoxypalladation by the principle of microscopic reversibility) would not permit acetate exchange in this system.



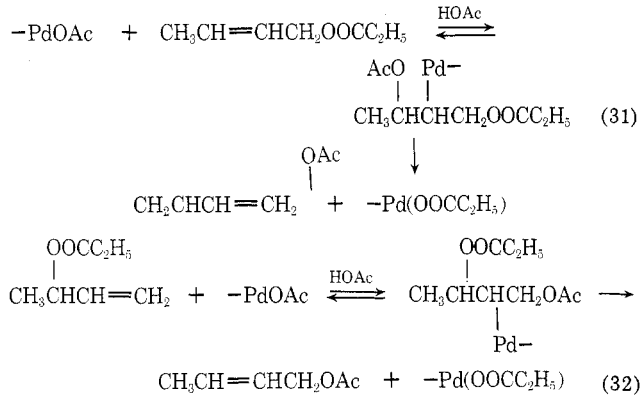
(30)

Thus the vinyl ester exchange studies produced the surprising result that acetoxypalladation is a stereochemically pure trans process, as opposed to the cis stereochemistry expected by analogy with the Wacker reaction. Another unexpected result was that a Pd(II) dimer π complex is the reactive species. This point is elaborated in the next section.

Allylic Ester Exchange and Isomerization

Vinyl and allylic ester exchange complement each other. Thus, unless optically active allylic esters are used, allylic ester exchange does not give information concerning stereochemistry of addition. However, exchange of unsymmetrical esters readily distinguishes

between SN2, π-allyl, and acetoxypalladation routes. The acetoxypalladation route would predict that exchange occurs only with isomerization of one allylic isomer into the other. For instance, crotyl propionate would exchange to give 2-buten-2-yl acetate (eq 31) while 3-buten-2-yl propionate would give crotyl



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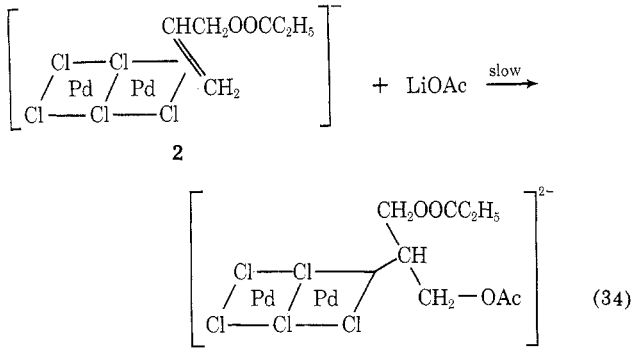
acetate (eq 32). The SN2 and π-allyl routes would predict different product distributions.[23]

The kinetics of the exchange were first studied using allyl propionate as the organic substrate.[24] The rate expression at low allyl propionate concentration is given by eq 33. This rate expression is exactly

$$\text{rate} = \frac{[Li_2Pd_2Cl_6][\text{allyl propionate}]}{[LiCl]} \times (k_2' + k_2''[LiOAc]) \quad (33)$$

analogous to that found for vinyl ester exchange, suggesting similar routes. The first step would be π-complex formation following by attack of acetate to give to the acetoxypalladation adduct, **3** (eq 34). Reversal of this step, eliminating $OOCC_2H_5$ instead of OAc, would complete exchange. However, a complication, not present in the vinyl ester exchange, was noted. This complication was inhibition of rate by the allyl propionate itself. In addition the product, allyl acetate, was about as effective an inhibitor as allyl propionate. By analysis of the kinetic data it could be shown that the inhibition arose from π-complex formation to give an *unreactive* monomeric π complex according to eq 35 where K_6 has a value of 0.25 M^{-1} for allyl propionate. This value of K_6 from kinetic measurements was confirmed by a spectral study. Since the kinetics require the dimeric π complex (see eq 23) to be the reactive species and this species could not be detected in appreciable concentration, the dimer π complex must be many times more reactive than the monomeric π complex. This difference is believed to result from electrostatic effects. In the rate-determining step of the reaction an acetate is attacking the π complex from outside the coordination sphere. The monomeric π complex would have considerably more negative charge on the Pd(II) containing the allyl ester than in the case of the dimeric π complex, **2**. The mutual repulsion of negative charge would tend to slow the rate of the monomeric π complex.



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(34)

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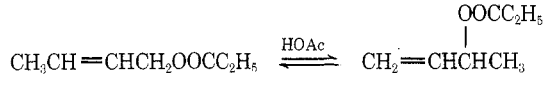
$$Li_2Pd_2Cl_6 + 2 \text{ allyl ester} \overset{K_6}{\rightleftharpoons} 2LiPdCl_3(\text{allyl ester}) \quad (35)$$

The exchange of the unsymmetrical esters, crotyl propionate and 3-buten-2-yl propionate, was now studied.[25] The reaction proved to be considerably more complicated than expected. By computer simulation of product distribution with time it could be shown that two separate reactions were taking place. One was the expected exchange reaction with a rate expression identical with that found for allyl propionate (eq 33). Furthermore it was shown that exchange occured only with isomerization of crotyl ester to 3-buten-2-ol ester and *vice versa*, a result expected for the acetoxypalladation mechanism (eq 31 and 32).

The unexpected reaction was isomerization without exchange (eq 36). It was found that, if crotyl



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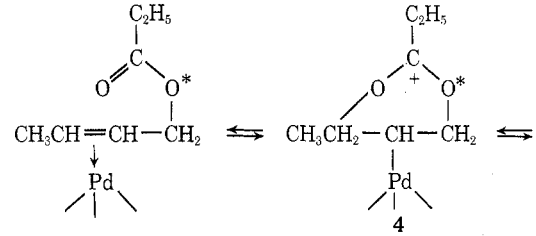
propionate with an ^{18}O label in the alcohol oxygen was isomerized, the 3-buten-2-yl propionate contained the label in the carbonyl oxygen. This result is consistent with exchange occurring *via* a 1,3-acetoxonium-type intermediate, **4**. Further evidence



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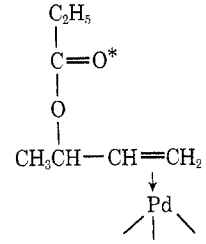


(37)

for this type of intermediate is provided by the effect of electron-withdrawing groups on rate. Thus if C_2H_5 is changed to CF_3, the rate of isomerization without exchange drops by a factor of 500. This effect on rate is consistent with a positively charged intermediate since electron-withdrawing groups would destabilize the acetoxonium ion intermediate. In the author's

(23) The SN2 mechanism would predict no isomerization, while the π-alkyl route would require that both alkylic propionates give the same distribution of allylic acetates.

(24) P. M. Henry, *J. Amer. Chem. Soc.*, 94, 1527 (1972).

(25) P. M. Henry, *J. Amer. Chem. Soc.*, 94, 5200 (1972).

knowledge this is the first example of an oxymetallation giving an unstable bridged intermediate such as 4.

Vinyl Chloride Exchange with Radioactive Chloride

This exchange, the first to be studied which involved exchanging species other than acetate, provided some new surprises.[26] First the rate expression is extremely simple. Most important, there was no indication of the LiCl inhibition term which would

$$CH_2{=}CHCl + LiCl^* \overset{Pd(II)}{\rightleftharpoons} CH_2{=}CHCl^* + LiCl \quad (38)$$

$$\text{rate} = k_3[Li_2Pd_2Cl_6][\text{vinyl chloride}] \quad (39)$$

be expected if π-complex formation were the initial

$$Li_2Pd_2Cl_6 + C_2H_3Cl \overset{K_7}{\rightleftharpoons} Li_2Pd_2Cl_5(C_2H_3Cl) + LiCl \quad (40)$$

step in the reaction. Second, the *cis*- and *trans*-1-chloropropenes isomerized into an equilibrium mixture much faster than they exchanged radioactive chloride from solution; therefore stereochemical information on the exchange reaction could not be obtained. Third, as shown by the data in Table II, 1-chlorocyclopentene exchanges at about the same rate as 2-chloro-2-butene.

(41)

Table II
Rate of Radioactive Exchange of Several Vinylic Chlorides at 25°

Vinylic chloride	k_3, M^{-1} sec^{-1}
$CH_2{=}CHCl$	10
$CH_3CH{=}CHCl$	0.23
$CH_3CH{=}C(CH_3)Cl$	0.049
1-Cyclopentenyl chloride	0.056

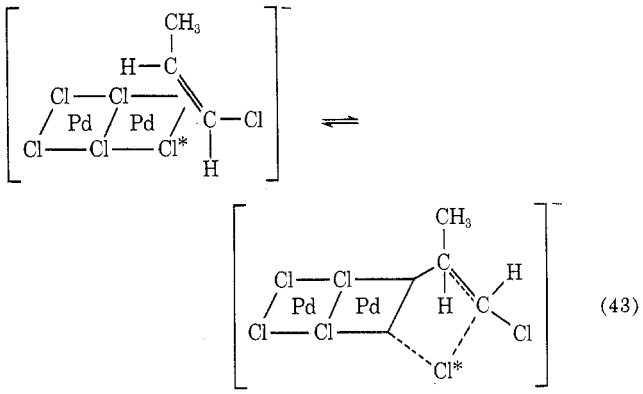
The fact that 1-chlorocyclopentene exchanges indicates that both cis and trans modes of chloropalladation are operative for, by the same arguments used for acetoxypalladation (see eq 30), if chloropalladation were stereochemically pure, cyclic vinylic chlorides should not exchange. Both modes of chloropalladation must have the rate expression of eq 39.

Since π-complex formation is almost certainly required for activation of vinylic chloride toward attack by chloride, the form of the rate equation most indicative of mechanism is eq 42, where all but the

$$\text{rate} = \frac{k_3[Li_2Pd_2Cl_6][\text{vinyl chloride}][LiCl]}{[LiCl]} \quad (42)$$

[LiCl] factor in the numerator is related to π-complex formation *via* eq 40.

The trans chloropalladation must occur by chloride attack from outside the coordination sphere, analogous to acetoxypalladation (eq 25). This type of attack would certainly cause the rate expression to have [LiCl] in the numerator. However the need for this [LiCl] factor in the rate expression for cis chloropalladation is not so obvious. Since cis chloropalladation must occur from the coordination sphere of the Pd(II), the [LiCl] factor most likely arises from the need to fill the incipient vacant coordination sphere on Pd(II). The scheme would be as given by eq 43 and 44. Exchange would be completed by de-



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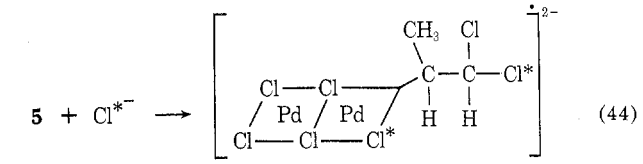


(44)

6

chloropalladation of nonradioactive chloride from 6.

Allylic Trifluoroacetate Exchange with Chloride

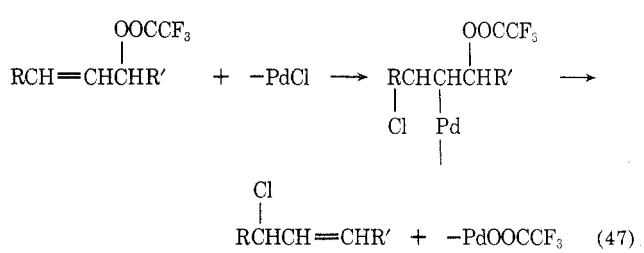
Following the procedure used previously, the next logical exchange to study would be the allyl chloride radioactive chloride exchange. However, as this exchange would be expected to follow a mechanism analogous to the vinyl chloride–chloride exchange, it seemed more instructive to study the exchange of one type of functional group for another. The allylic trifluoroacetate exchange for chloride (eq 45), a reaction which goes to completion even at low chloride concentration, was chosen.[27]

$$CH_2{=}CHCH_2OOCCF_3 + LiCl \xrightarrow{Pd(II)} CH_2{=}CHCH_2Cl + LiOOCCF_3 \quad (45)$$

The rate expression (eq 46) is analogous to that

$$\text{rate} = k_4[Li_2Pd_2Cl_6][C_3H_5O_2CCF_3] \quad (46)$$

found for vinylic chloride–chloride exchange, suggesting that the rate-determining step is chloropalladation. In support of the chloropalladation–detrifluoroacetoxypalladation mechanism are the re-



(47)

(26) P. M. Henry, *J. Org. Chem.*, 37, 2443 (1972).

(27) P. M. Henry, *Inorg. Chem.*, 11, 1876 (1972).

sults of exchange of crotyl and 3-buten-2-yl trifluoroacetate. Each exchanges only with isomerization, a result expected on the basis of this mechanism (R, R′ = CH_3 or H).

Vinyl Chloride Exchange with Acetate

To complete the cycle of acetate and chloride exchanges the exchange of vinyl chloride with acetate was studied.[28] This exchange has previously been studied by several workers[18,29-32] and it has been reported that, at least qualitatively, with *cis*- and *trans*-1-chloropropene exchange occurs with retention of configuration. Thus *cis*-1-chloropropene gives mainly *cis*-1-acetoxypropene. This result led to the suggestion[33] that exchange occurs by an acetoxypalladation–dechloropalladation mechanism (eq 17 and 18, X = Cl and Y = OAc), in which acetoxypalladation has the opposite stereochemistry from dechloropalladation.

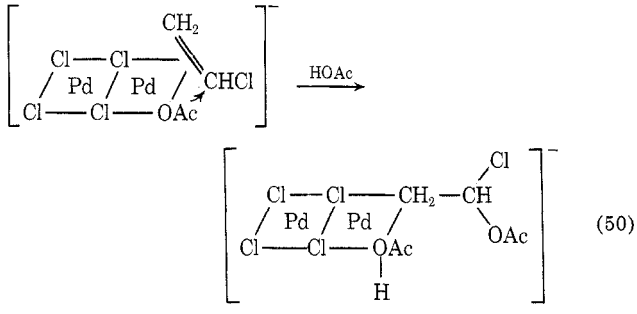
The previous qualitive reports[18,32] of the stereochemistry of *cis*- and *trans*-1-chloropropene exchange was checked in a quantitative fashion in the present work. It was found that in fact the stereochemical results are not pure. Thus *cis*-1-chloropropene gives a mixture of *cis*- and *trans*-1-acetoxypropene, but the mixture is mainly cis (85%) with the remainder trans. *trans*-1-Chloropropene gave mainly *trans*-1-acetoxypropene.

Rate expression 48 is the first to exhibit a squared

$$\text{rate} = [Li_2Pd_2Cl_6][\text{vinyl chloride}]/[LiCl]^2 \times (k_5' + k_5''[LiOAc]) \quad (48)$$

inverse dependence on [LiCl]. The similarity of this rate expression to that for the Wacker reaction (eq 10) suggests that acetoxypalladation is occurring by attack of coordinated acetate on coordinated olefin.

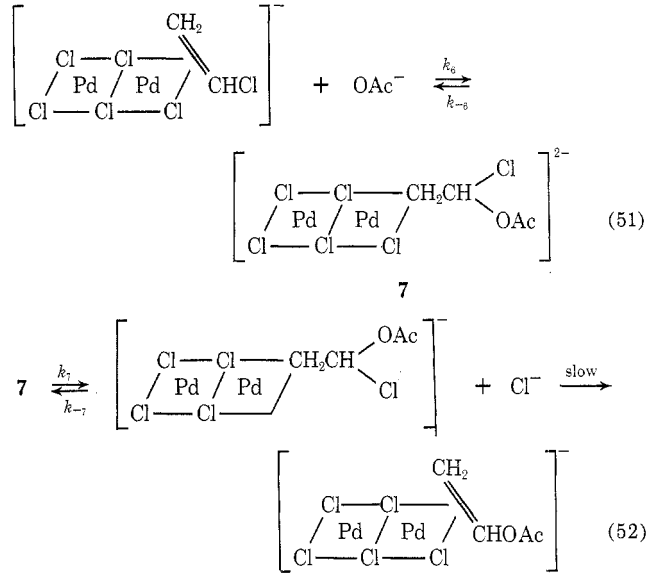
$$Li_2Pd_2Cl_6 + C_2H_3Cl + LiOAc \rightleftharpoons LiPd_2Cl_4(C_2H_3Cl)(OAc) + LiCl \quad (49)$$



(50)

However, acetoxypalladation of vinyl and allylic esters does not occur by this route, and there is no reason to expect that vinyl chloride should react so differently from vinyl acetate.

In fact, a mechanism can be written which is entirely consistent with both previous and present kinetic and stereochemical results. The first step is, of course, π-complex formation *via* eq 40. The following steps are given by eq 51 and 52. The important point



(51)

(52)

is that for dechloropalladation to occur (eq 52) a vacant coordination site must be present on the Pd(II). Thus LiCl inhibition would appear in both eq 40 and 52, accounting for the squared LiCl inhibition factor. The kinetics also require that eq 51 be reversible since eq 52 must be the rate-determining step.

The stereochemical results with *cis*- and *trans*-1-chloropropene indicate that not all dechloropalladation occurs by cis elimination. This result is consistent with the radioactive exchange studies on vinyl chlorides which indicate that chloropalladation is also not stereospecific. By the principle of microscopic reversibility, dechloropalladation should also be nonstereospecific.

Table III
Rates of Acetate Exchange of Several Vinylic Chlorides

Vinylic chloride	$k_1 \times 10^4$, sec^{-1}
CH_2=CHCl	1.94
trans-CH_3CH=CHCl	1.5×10^{-2}
CH_3CH=$C(CH_3)$Cl	2.2×10^{-4}
1-Cyclopentenyl chloride	2.6×10^{-3}

Table III lists the rate of exchange of several vinylic chlorides. As with previous exchanges methyl substitution on vinylic carbon strongly depresses rate, a result consistent with a large steric requirements for acetoxypalladation. The most interesting result, however, is the fact that 1-chlorocyclopentene reacts over ten times faster than 2-chloro-2-butene. As shown in Table I the rate of exchange of 1-acetoxycyclopentene was much slower than that of 2-acetoxy-2-butene, a result consistent with stereospecific acetoxypalladation (eq 30). In the case of radioactive chloride exchange, however, the rates for the cyclic and straight vinylic chlorides are about equal. Now 2-chloro-2-butene must exchange one-half the time it chloropalladates. 1-Chlorocyclopentene, on the other hand, exchanges less than one-half the times it chloropalladates because chloropalladation is mainly cis. Thus cis chloropalladation–cis dechloropalladation, which cannot give exchange, is preferred over cis

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(32) E. W. Stern, *Catal. Rev.*, 1, 73 (1967); see p 125.
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chloropalladation–trans dechloropalladation or trans chloropalladation–cis dechloropalladation. The latter two routes give exchange. This analysis requires chloropalladation of 1-chlorocyclopentene to be faster than 2-chloro-2-butene. Finally, since acetoxypalladation has opposite stereochemistry from chloropalladation, the rates of exchange of the straight chain and cyclic vinylic chlorides should be close to the ratio of their rates of acetoxypalladation. As expected from the radioactive chloride results, 1-chlorocyclopentene exchanges chloride for acetate faster than 2-chloro-2-butene.

The first series of chloride and acetate exchanges in acetic acid catalyzed by Pd(II) in chloride-containing media present a consistent picture and elucidate some of the factors involved in acetoxypalladation and chloropalladation. Kinetics of exchange and other stereochemical evidence indicate acetoxypalladation to be a pure trans process while chloropalladation is mainly cis but occurs trans about 15% of the time. In retrospect this result is not surprising since in this system chloride is much more strongly complexed to Pd(II) than is acetate. Thus chloride is in position for a cis attack while acetate is not. Both chloride and acetate, however, are able to attack trans.

The important conclusion is that the stereochemistry of addition of metal ions and nucleophiles across double or triple bonds is not absolute for a given metal ion; rather, it depends on subtle factors such as coordination between nucleophile and the metal ion. Thus phenylpalladium, which is almost certainly a covalently bonded species, adds cis to cyclohexene.[34] On the other hand uncoordinated amines add trans to Pt(II)–monoolefin complexes.[35] Attack of nucleophiles on Pd(II)- and Pt(II)–diolefin complexes has also been found to be trans.[36-38] Among other factors, the fact that the diolefin occupies two coordination positions, thus preventing coordination of nucleophile, may be important.

Another well-studied metal ion addition to unsaturated double bonds is that of Hg(II) and nucleophiles. With simple olefins such as cyclohexene the addition of H_2O, acetate, and methanol is trans while addition to strained olefins such as norbornene is mainly cis[39,40] but depends somewhat on the olefin used.[41] However, dechloromercuration of olefins, which has not been studied to any extent, might well be cis. Thus exchange of cis and trans 1-chloropropene catalyzed by Hg(II) may well give stereochemical results similar to Pd(II).

Another result worthy of note is the need to fill an incipient coordination site on Pd(II) before cis chloropalladation can be achieved and conversely the need for an open coordination sphere on Pd(II) before dechloropalladation can be completed. The need for a vacant coordination site on a metal is a very important feature of homogeneous catalysis,[16] and the present results indicate this requirement to be very important in cis insertion processes.

Acid-Catalyzed Allylic Exchange

During the course of study of the effect of allylic propionate structure on rate of exchange with acetic acid, it was observed that 2-cyclohexene-1-yl propionate exchanged at a very slow rate even at 1.0 *M* LiOAc concentration. This rate was much slower than would be expected from steric effects. Even more surprising, the rate of exchange was faster when the LiOAc was omitted. Thus acetate has an inhibitory effect on this exchange as opposed to the catalytic effect on all the other acetate exchanges studied! This result suggested that the exchange is acid catalyzed. Acid catalysis was confirmed by runs at various [LiOAc] as well as by runs in which CF_3COOH was added to the reaction mixture.[42] The rate expression for the exchange is given by eq 53

$$\text{rate} = ([Li_2Pd_2Cl_6][\text{allyl ester}](k_N + k_A[\text{acid}]) \quad (53)$$

where k_N is the rate constant for the neutral reaction and k_A the rate constant for the acid-catalyzed reaction.

Two questions concerning this reaction must be answered. First, why is the cyclic allylic ester so much less reactive than straight allylic esters in the conventional acetate-catalyzed reaction; second, which is the mechanism of the acid-catalyzed reaction? The answer to the first question may lie in the conformational energies of the cyclohexene system, but the arguments are too complicated for a short review.

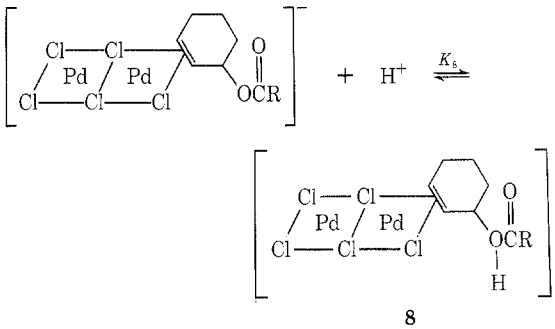
As to the mechanism of this new acid-catalyzed exchange, the rate expression does not contain the [LiCl] inhibition factor required for the formation of π complex (eq 54). As in previous cases where this

$$Li_2Pd_2Cl_6 + \text{allyl ester} \rightleftharpoons LiPd_2Cl_5(\text{allyl ester}) + LiCl \quad (54)$$

factor did not appear, its absence is very likely due to cancellation by a [LiCl] factor in the denominator. The correct rate expression is that of eq 55.

$$\text{rate} = \frac{[Li_2Pd_2Cl_6][\text{allyl ester}][LiCl]}{[LiCl]}(k_N + k_A[\text{acid}]) \quad (55)$$

Of the mechanisms which can be written for this exchange, one intriguing possibility involves a Pd(IV) π-allyl. The acid catalysis would result from proto-



(56)

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(39) T. G. Traylor and A. W. Baker, *Tetrahedron Lett.*, 14 (1959).
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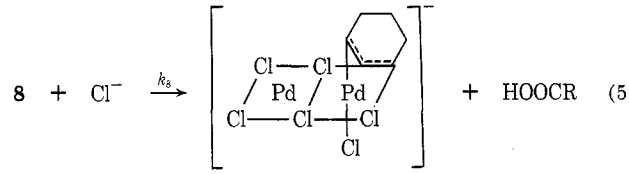
(41) T. G. Traylor, *Accounts Chem. Res.*, 2, 152 (1969).
(42) P. M. Henry, submitted for publication.

nation of the alcohol oxygen in the allylic ester, thus weakening the carbon–oxygen bond. The rate-determining step would be oxidative addition to give a Pd(IV)–π-allyl. The [LiCl] term in the numerator would result from the need to fill in the sixth coordi-



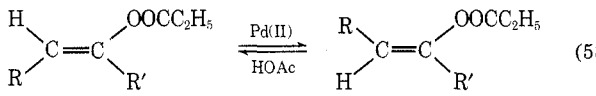
(57)

nation position on d^6 Pd(IV). Reversal of the oxidative addition would then give exchange.

Whatever the exact mechanism, this result indicates that the acetoxypalladation route is not the only means of allylic ester exchange. Further studies aimed at defining the exact mechanism of the acid-catalyzed reaction are planned. In particular, stereochemical studies should differentiate between the various possible reaction paths.

Cis–Trans Isomerization

In the discussion of radioactive chloride exchange of vinylic chlorides mention was made of a side reaction involving cis–trans isomerization without exchange with radioactive LiCl (eq 41).[26] *cis*- and *trans*-1-bromopropene were also isomerized without exchange of chloride for bromide.[43] Cis–trans isomerization without exchange was also observed in acetate-exchange studies with enol esters, although it was a less serious side reaction in this case. The isomerization was observed with the enol propionates

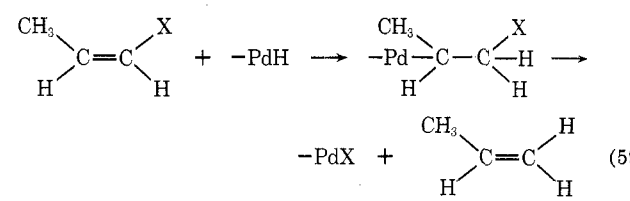


(58)

of propionaldehyde (R = CH_3, R′ = H), phenylacetaldehyde (R = C_6H_5, R′ = H) and 2-butanone (R = R′ = CH_3).

There have been many reports of double bond and cis–trans isomerizations catalyzed by noble metal salts. The mechanisms suggested for these reactions include intermolecular hydride transfer *via* metal hydrides, intramolecular hydride transfer *via* π-allyl hydrides, and reversible π-allyl complex formation. However, the isomerizations described in this work do not appear to proceed by any of these routes. Thus the π-allyl routes can be eliminated because the enol propionates of phenylacetaldehyde, which do not have allylic hydrogens, are isomerized.

The reactions also do not exhibit any of the features expected of hydride mechanisms such as exchange of hydrogens with deuterated solvent or deuterated olefins, acid catalysis, or double bond isomerization. In fact, if palladium(II) hydride is generated *in situ*, isomerization is not observed. The only reaction is decomposition of the enol propionate or vinylic halide *via* eq 59 (X = $OOCC_2H_5$, Cl, or Br).



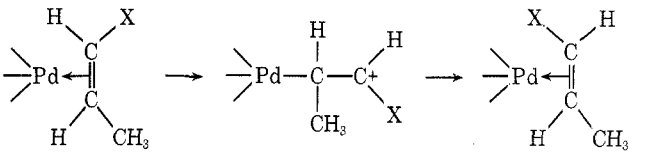
(59)

It thus appears that the mechanisms usually considered for Pd(II)-catalyzed isomerization are not operative in the present examples. The general rate expression for the isomerization is given in eq 60.

$$\text{rate} = (k_9[Li_2Pd_2Cl_6]/[LiCl] + k_{10}[Li_2Pd_2Cl_6] + k_{11}[Li_2Pd_2Cl_6]^{1/2})[\text{olefin}] \quad (60)$$

The enol propionate isomerization displays only the k_9 term,[20] the vinylic chloride isomerization has all three terms, while the vinylic bromide isomerization has the k_{10} and k_{11} terms.[44]

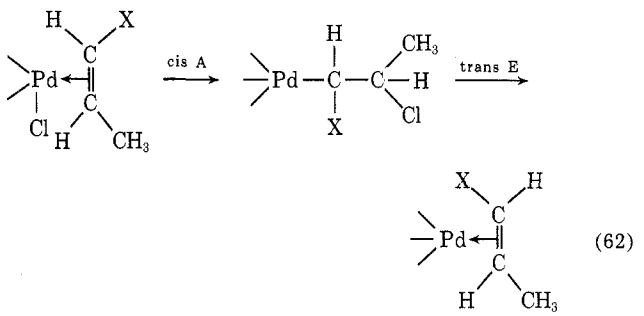
The k_9 term corresponds to π-complex formation *via* eq 23 while the k_{11} term[45] corresponds to π-complex formation *via* eq 24. Isomerization *via* the π complexes must be accomplished without the intervention of an external reagent. A definite mechanism cannot be proposed on the basis of the evidence to date, but an attractive one is a π–σ rearrangement to give a Pd(II)-bonded carbonium ion with sufficient lifetime for rotation (X = $OOCC_2H_5$, Cl, or Br).



(61)

This mechanism will be tested by determining the effect of electron-releasing and -withdrawing substituents on the isomerization. A mechanism such as that represented by eq 61 would predict a large negative ρ.

The k_{10} term is of the same form as previously found for chloropalladation (eq 40), which suggests that isomerization may occur by nonstereospecific chloropalladation–dechloropalladation in the fashion reversed from that which gives exchange (A = addition, E = elimination).



(62)

This mechanism is being tested by studying the isomerization and radioactive chloride exchange of the cis and trans isomers of 1,2-dichloroethylene. Chloropalladation of this olefin must result in exchange, so the k_{10} term in eq 60 must correlate with exchange rate if this term results from nonstereospecific chloropalladation.

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(45) It is interesting that this is the first reaction in this series in which the monomeric π complex is a reactive species. The results advanced for the inactivity of this π complex in the exchange reactions are not valid in the case of isomerization since isomerization does not involve the attack of an external nucleophile.

Conclusions

As an example of the type of information which can be obtained in exchange studies, some representative results with just one system have been described. As well as defining the detailed mechanisms of acetoxypalladation and chloropalladation, these studies have revealed three new reactions, the allylic and cis–trans isomerizations and the acid-catalyzed exchange.

However, it is well to point out that, besides their own intrinsic interest, these studies should help in elucidating the mechanisms of other Pd(II)-catalyzed reactions. As an example, consider the oxidation of ethylene in HOAc. A general mechanism for vinyl ester formation consistent with other Pd(II) chemistry is given by eq 63–67 (X = OAc, Cl, etc.).

$$PdX_4^{2-} + C_2H_4 \underset{k_{-12}}{\overset{k_{12}}{\rightleftharpoons}} PdX_3(C_2H_4)^- + X^- \quad (63)$$

$$PdX_3(C_2H_4)^- + OAc^- \underset{k_{-13}}{\overset{k_{13}}{\rightleftharpoons}} X_3Pd-CH_2CH_2OAc \quad (64)$$

$$^{2-}X_3Pd-CH_2CH_2OAc \xrightarrow{k_{14}} {}^{2-}X_3PdH + CH_2=CHOAc \quad (65)$$

$$^{2-}X_3Pd-CH_2CH_2OAc \underset{k_{-15}}{\overset{k_{15}}{\rightleftharpoons}} {}^{-}X_2Pd-CH_2CH_2OAc + X^- \quad (66)$$

$$^{-}X_2Pd-CH_2CH_2OAc \xrightarrow{k_{16}} {}^{-}X_2PdH + CH_2=CHOAc \quad (67)$$

The last two equations represent the possibility that palladium(II) hydride elimination does not occur until a negative ligand is lost. This possibility must be considered since a vacant coordination position might well be a prerequisite for palladium(II) hydride elimination. This need for a vacant coordination site has precedent in the dechloropalladation step of vinyl chloride exchange with acetate.

If reaction 64 is the rate-determining step, of course the kinetics would give no information on eq 65–67. However if it were not, in principle we could determine if decomposition required the loss of X from the coordination sphere of Pd(II). In either case the kinetics would be difficult to interpret because the exact steps in arriving at $X_3PdCH_2CH_2OAc$ are not known. However, the acetoxypalladation reaction would be expected to be similar for ethylene and vinyl propionate. Furthermore, we know that the rate-determining step for exchange must be eq 25 since exchange must occur approximately one-half the time acetoxypalladation occurs.[46] Thus, by comparison of the rate expressions for exchange and oxidation, the rate-determining step for the latter should be more readily deduced.

(46) The tendencies of OAc and OOCR to be lost from an intermediate such as 1 (eq 25) must be about equal.

Future Work

In regard to the $PdCl_2$–LiCl system in acetic acid the Pd(II)-catalyzed saponification of vinyl esters in wet acetic acid is being studied. A previous study[47] of this system indicated that a hydroxypalladation

$$RCH{=}CHOAc + H_2O \underset{HOAc}{\overset{PdCl_2-LiCl}{\rightleftharpoons}} RCH_2CHO + HOAc \quad (68)$$

mechanism is operative. However, because the various equilibria were not defined, the exact mode of hydroxypalladation was unclear. The present studies are aimed at elucidating the exact mechanism. This system is particularly complicated because water is not only a reactant but, in addition, it changes the solvent power of the acetic acid and thus affects the various equilibria in the system.

As indicated earlier, the cis–trans isomerization requires more study, as does the acid-catalyzed exchange. Work aimed at defining the generality of the allylic isomerization is planned: how many neighboring groups are capable of performing this isomerization and what other types of shifts, such as 1,2 shifts, take place?

Work has begun on a different system, the $Pd(OAc)_2$–NaOAc or –LiOAc system in HOAc. This chloride-free system is of particular interest because of two experimental observations. First, product distributions for oxidation of 1-olefins change with acetate concentration. For example, at low acetate concentration propylene gives isopropenyl acetate while at higher acetates the main product is allyl acetate.[48-51] Second, the rate of oxidation of ethylene has a complicated dependence on [NaOAc], first increasing with increasing [NaOAc] to about 0.3 *M* and then decreasing with further increase in [NaOAc].[15] Equilibrium and exchange studies should shed some light on these anomalies. Perhaps, as discussed earlier, the studies of the kinetics of oxidation and exchange will supplement each other.

Finally the work will be extended to other solvents such as methanol. Methanol lies between acetic acid and water in solvent characteristics and thus exchanges in it may be expected to exhibit intermediate mechanistic behavior.

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(51) J. E. McCaskie, Ph.D. Thesis, University of California, Los Angeles, Calif., 1971.