

# Carbon-Carbon Bond Formation *via* Palladium Complexes

JIRO TSUJI

Basic Research Laboratories, Toyo Rayon Co., Ltd., Kamakura, Japan

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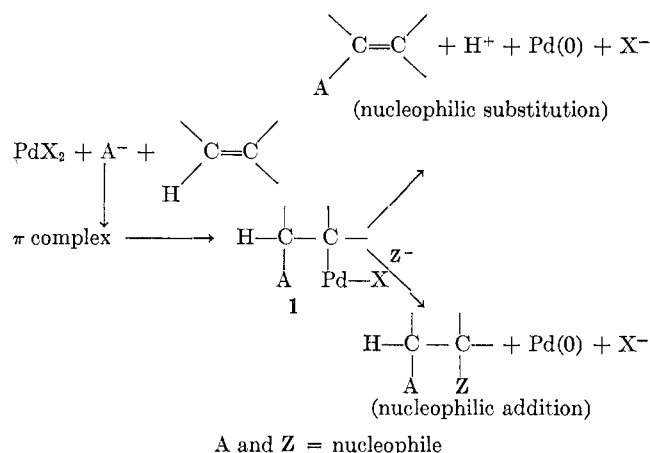
In recent years, remarkable advances in organic syntheses *via* transition metal complexes have occurred. Among the transition metal complexes used for organic syntheses, those of palladium have had a unique position since 1960. For a long time, palladium had been used in organic synthesis only as a catalyst for hydrogenation. After the epoch-making introduction in 1960 of the Wacker process, by which acetaldehyde is produced from ethylene using palladium as a catalyst,<sup>1,2</sup> palladium was recognized as a versatile reagent for organic syntheses. Since then, many synthetic reactions using palladium have been discovered.<sup>3</sup>

We have been working on organic syntheses *via* palladium complexes, especially studies aimed at finding new methods for carbon-carbon bond formation. In this Account, our studies directed toward carbon-carbon bond formation are treated, with related studies carried out by other workers.

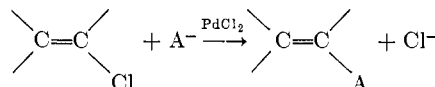
## Some Features of Reactions Involving Palladium

In synthetic reactions involving palladium, activation of simple molecules such as H<sub>2</sub>, CO, olefins, acetylenes, aromatic compounds, and other compounds having active hydrogens takes place through coordination. Pd(II) is reduced to the zerovalent state easily, oxidizing coordinated molecules, and by this property, unique oxidation with Pd(II) is possible. When coordinated with Pd(II), for example, an olefinic bond, which when not complexed is usually susceptible to electrophilic attack, now reacts with nucleophiles and undergoes palladation reactions. In the palladation reaction, a ligand, A, on palladium migrates to a  $\pi$ -bonded olefin which simultaneously is transformed into a  $\sigma$ -bonded complex (1). The palladium  $\sigma$  bond is reactive and undergoes decomposition or further transformations. Usually insertion reactions<sup>4</sup> take place before the final decomposition of the  $\sigma$  complexes.

In the wake of the palladation reaction, Pd(II) accepts two electrons and is converted into Pd(0). Thus by reaction of the palladium-olefin complex with nucleophiles which contribute, for example, OH, OR, OCOCH<sub>3</sub>, amine, and carbanion residues, it is possible to prepare vinyl compounds by substitution on the vinyl carbon. In some cases, nucleophilic addition to



give bifunctional products is possible.<sup>5</sup> Also, a halogen atom linked to olefinic carbon (for example, in vinyl chloride) can be replaced by a nucleophile in the presence of a catalytic amount of Pd(II).<sup>6-8</sup>



These vinylation and additions are special features of reactions using Pd(II) and are very useful in organic syntheses. Not only  $\pi$ -olefin bonds, but also  $\pi$ -allylic complexes and palladium  $\sigma$  bonds are attacked by nucleophiles. Besides olefinic hydrogens, the oxidative displacement of aromatic hydrogen is also possible.

Pd(0) complexes also catalyze useful reactions. In these, a covalent molecule as a reactant adds to the coordination sphere of coordinatively unsaturated Pd(0) complexes. By this oxidative addition<sup>9</sup> to Pd(0), the valence state of Pd(0) increases by two units, and then insertion of various molecules takes place. It should be noticed that the product of the insertion reaction (step 2) is somewhat similar to the product of the palladation reaction (step 1) mentioned above. Finally Pd(0) is regenerated by reductive elimination, thus making the whole reaction catalytic. In this sense, it can be said that palladium is easily oxidized and then reduced. In other words, palladium has a useful ability to supply and accept electrons. Although palladium is considered to be a

(1) J. Smidt, W. Hafner, R. Jira, R. Sieber, J. Sedlmeier, and A. Sabel, *Angew. Chem.*, **74**, 93 (1962); *Angew. Chem. Intern. Ed. Engl.*, **80** (1962); *Chem. Ind. (London)*, 54 (1962).

(2) A. Aguilo, *Advan. Organometal. Chem.*, **5**, 321 (1967).

(3) For reviews: (a) J. Tsuji, *Advan. Org. Chem.*, **6**, in press; (b) E. W. Stern, *Catalysis Rev.*, **1**, 74 (1968).

(4) R. F. Heck, "Insertion Reactions of Metal Complexes," *Advances in Chemistry Series*, No. 49, American Chemical Society, Washington, D.C., 1965, p 181.

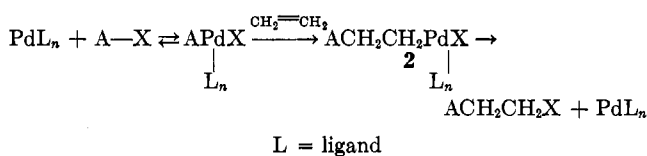
(5) For a typical example: C. F. Kohll, T. Jonkhoff, and R. van Helden, Netherlands, Appl., 301519 (1965); *Chem. Abstr.*, **64**, 6502 (1966).

(6) E. W. Stern, M. L. Spector, and M. P. Leftin, *J. Catalysis*, **6**, 152, (1966).

(7) C. F. Kohll and R. van Helden, *Rec. Trav. Chim.*, **87**, 481 (1968).

(8) H. C. Volger, *ibid.*, **87**, 501 (1968).

(9) For oxidative addition reactions, see the following review: J. P. Collman, *Accounts Chem. Res.*, **1**, 136 (1968).



noble metal, it is not an inert metal. For example, we have found that metallic palladium is oxidized to its divalent chloride complex in the presence of hydrogen chloride, which undergoes oxidative addition, and some suitable ligand such as phosphine or cyclooctadiene.<sup>10,11</sup>

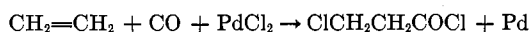
The importance of the oxidative addition to Pd(0) complexes is closely related to chemisorption on metallic palladium catalyst. No doubt there is a close mechanistic analogy between homogeneous (coordination and oxidative addition) and heterogeneous (chemisorption) palladium catalysts in respect to their reactions with H<sub>2</sub>, HX, CO, olefins, etc. Studies on the catalytic activities of Pd(0) certainly afford clues to understanding the boundary between heterogeneous and homogeneous catalyses.

Palladium has a strong affinity for hydrogen. In many palladium-catalyzed reactions, intermolecular and intramolecular hydrogen shifts take place through Pd-H bond formation.

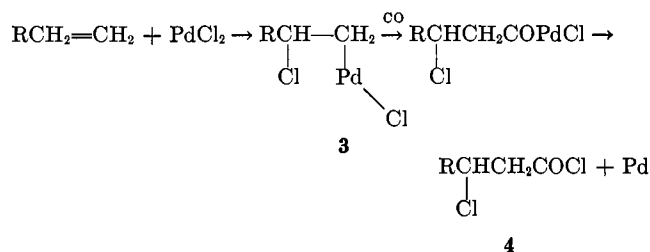
### Carbonylation and Decarbonylation Reactions

Carbon monoxide reacts with various olefinic and acetylenic compounds to form carbonyl compounds in the presence of either Pd(II) (stoichiometric) or Pd(0) (catalytic).

**Carbonylation of Olefins.** The reaction of the ethylene-palladium chloride complex with CO in benzene proceeds smoothly at room temperature, and the product is  $\beta$ -chloropropionyl chloride.<sup>12,13</sup> When

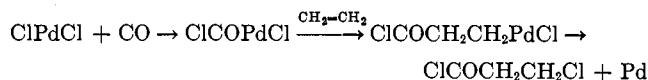


the reaction is carried out in ethanol, ethyl  $\beta$ -ethoxypropionate is formed.<sup>14</sup> The following mechanism was proposed for this addition reaction. Insertion (palladation) of the coordinated olefin into the palladium-chlorine bond (or nucleophilic attack of Cl) forms a  $\beta$ -chloroalkyl palladium complex (3). This complex

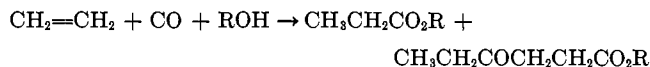


undergoes CO insertion to form an acyl-palladium complex (4). The final step is the formation of  $\beta$ -chloroacyl chloride by reductive elimination of the acyl group and the chlorine.

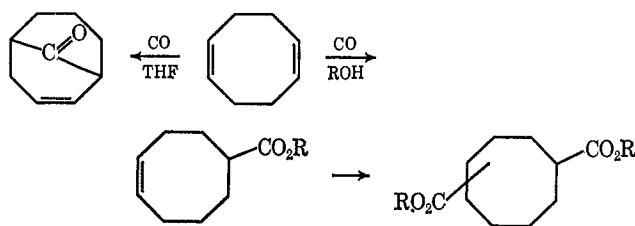
Another possibility is CO insertion into the Pd-Cl bond, followed by olefin insertion (palladation).<sup>15</sup>



In the course of studies on the reaction of CO with olefin complexes in alcohol, we have found that carbonylation of olefins can be carried out in alcohol and that the product is a saturated ester.<sup>16</sup> In this carbonylation reaction, only a catalytic amount of palladium is necessary. It was found that the essential catalyst for the reaction is Pd(0) plus hydrogen halide. Thus from the reaction of ethylene with CO (40 atm) in ethanol containing HCl at 100°, ethyl propionate is obtained as a main product, and ethyl 4-ketohexanoate as a minor product.<sup>16</sup>



When olefins other than ethylene are carbonylated, the products are a mixture of normal and iso esters, and in general the iso ester predominates. Also the carbonylation can be carried out by using PdCl<sub>2</sub>-[P(C<sub>6</sub>H<sub>5</sub>)<sub>3</sub>]<sub>2</sub> and HCl as the catalyst.<sup>17</sup> The phosphine complex has high catalytic activity and is especially useful with substituted olefins. The carbonylation of cyclooctadiene can be carried out in the presence of a catalytic amount of PdCl<sub>2</sub> at 100° under CO (50 atm) in ethanol to give ethyl 4-cyclooctenylcarboxylate and cyclooctanedicarboxylate (60–90% yield).<sup>18</sup> Also, cyclooctadiene in tetrahydrofuran reacts with CO at 150° and 1000 atm in the presence of PdI<sub>2</sub>[P(C<sub>4</sub>H<sub>9</sub>)<sub>3</sub>]<sub>2</sub> to give bicyclo[3.3.1]non-2-en-9-one in 45% yield.<sup>19</sup>



Carbonylation of norbornadiene in ethanol in the presence of a catalytic amount of PdCl<sub>2</sub> gave polyketone, formed by 1:1 copolymerization of CO and norbornadiene.<sup>20</sup>

Reaction of an olefin, CO, and H<sub>2</sub>, catalyzed by pal-

(10) J. Tsuji and K. Ohno, *J. Am. Chem. Soc.*, **90**, 94 (1968).

(11) F. Cariati, R. Ugo, and F. Bonati, *Inorg. Chem.*, **5**, 1128 (1966).

(12) J. Tsuji, M. Morikawa, and J. Kiji, *Tetrahedron Letters*, 1061 (1963).

(13) J. Tsuji, M. Morikawa, and J. Kiji, *J. Am. Chem. Soc.*, **86**, 8451 (1964).

(14) J. Tsuji, unpublished results.

(15) This possibility was suggested to the author by Drs. H. G. Tennent and P. M. Henry.

(16) J. Tsuji, M. Morikawa, and J. Kiji, *Tetrahedron Letters*, 1437 (1963).

(17) K. Bittler, N. V. Kutepow, D. Neubauer, and H. Reis, *Angew. Chem.*, **80**, 352 (1968).

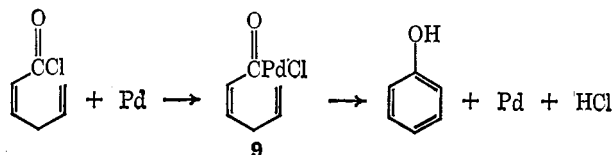
(18) J. Tsuji, S. Hosaka, T. Susuki, and J. Kiji, *Bull. Chem. Soc. Japan*, **39**, 141 (1966).

(19) S. Brewis and P. R. Hughes, *Chem. Commun.*, **6** (1966).

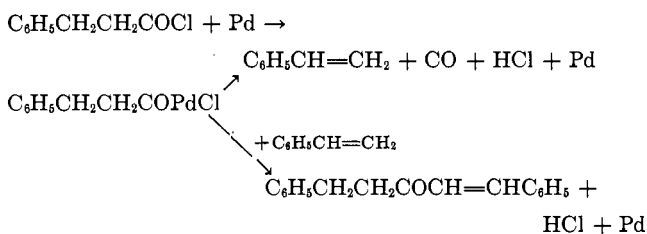
(20) J. Tsuji and S. Hosaka, *Polymer Letters*, **3**, 703 (1965).



acyl-palladium complex (9).

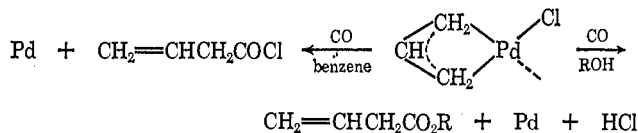


Intermediate formation of an acyl complex in the decarbonylation of acid chlorides is supported by the isolation of 1,5-diphenyl-1-penten-3-one as a minor product from phenylpropionyl chloride.<sup>10</sup> Thus Pd(0)



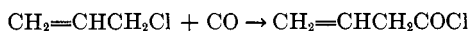
is a catalyst with special utility both for carbonylation in the presence of CO and decarbonylation in the absence of CO.<sup>27</sup>

**Carbonylation *via*  $\pi$ -Allylic Complexes.**  $\pi$ -Allylpalladium chloride is carbonylated at about 100° to form 3-butenolate esters in alcohol.<sup>28</sup> When the reaction is carried out in benzene, 3-butenoyl chloride is



the product. On the other hand, the carbonylation of some allylic compounds can be carried out catalytically.<sup>29,30</sup> Various allylic halides, alcohols, ethers, or esters can be carbonylated in the presence of a catalytic amount of PdCl<sub>2</sub> or other complexes. Carbonylation of allylic chlorides is best carried out in tetrahydrofuran (88% yield) in which the formation of free HCl is suppressed by a ring-opening reaction with tetrahydrofuran.<sup>29</sup>  $\pi$ -Allylpalladium complexes with phosphine ligands seem to be the best catalysts for the carbonylation of allyl chloride.<sup>31</sup>

When carbonylation is carried out in an aprotic solvent such as benzene or ethers, CO is inserted at the allylic position. Thus allyl chloride gives 3-butenoyl chloride, and allyl ethers form the corresponding esters. Allyl acetate gives the mixed anhydride of 3-butenic acid and acetic acid. In the



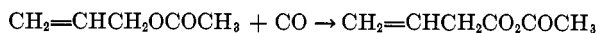
(27) Smooth and homogeneous decarbonylation is possible by using rhodium complexes: K. Ohno and J. Tsuji, *J. Am. Chem. Soc.*, **90**, 99 (1968).

(28) J. Tsuji, J. Kiji, and M. Morikawa, *Tetrahedron Letters*, 1811 (1963).

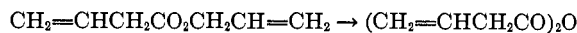
(29) J. Tsuji, J. Kiji, S. Imamura, and M. Morikawa, *J. Am. Chem. Soc.*, **86**, 4350 (1964).

(30) W. T. Dent, R. Long, and G. H. Whitfield, *J. Chem. Soc.*, 1588 (1964).

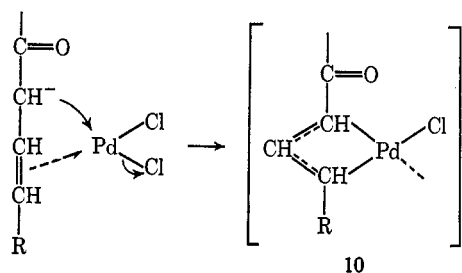
(31) D. Medema, R. van Helden, and C. F. Kohll, Symposium on New Aspects of the Chemistry of Metal Carbonyls and Derivatives, Venice, Sept 1968, and private communication from Dr. R. van Helden.



carbonylation of diallyl ether, allyl 3-butenolate is formed by the first CO insertion; the second CO insertion gives the anhydride of 3-butenic acid.

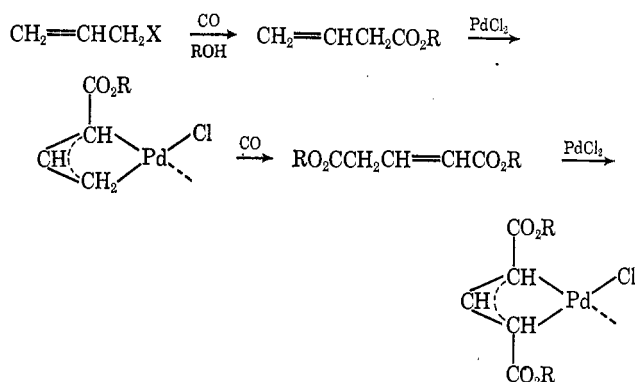


The products obtained by these carbonylations of allylic compounds are  $\beta,\gamma$ -unsaturated esters. A new  $\pi$ -allylic complex (10) can be formed from the  $\beta,\gamma$ -unsaturated esters by reaction with PdCl<sub>2</sub> and elimination of HCl.<sup>32,33</sup> Any compound having an allylic



hydrogen activated by an electron-attracting group, and thus capable of giving a carbanion, undergoes this type of complex formation.<sup>34</sup>

Carbonylation of the complex prepared from 3-butenolate gives glutaconate, which forms another  $\pi$ -allylic complex. Thus the following sequence of complex formation and carbonylation is possible.<sup>32</sup>



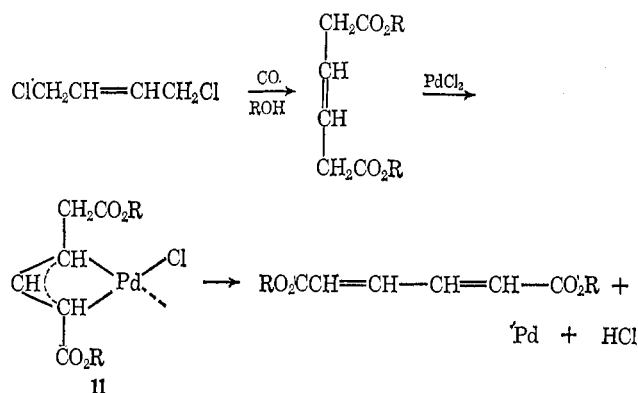
Another interesting application of complex formation is the oxidation of ethyl 3-hexenedioate, which is obtained by carbonylation of 1,4-dichloro-2-butene.<sup>35</sup> The hexenedioate forms  $\pi$ -allylic complex 11 easily. Treatment of this complex with base forms an anion from which palladium is reductively eliminated to give muconate. This oxidation can be made catalytic by use of PdCl<sub>2</sub> and CuCl<sub>2</sub>.

(32) J. Tsuji, S. Imamura, and J. Kiji, *J. Am. Chem. Soc.*, **86**, 4491 (1964).

(33) J. Tsuji and S. Imamura, *Bull. Chem. Soc. Japan*, **40**, 197 (1967).

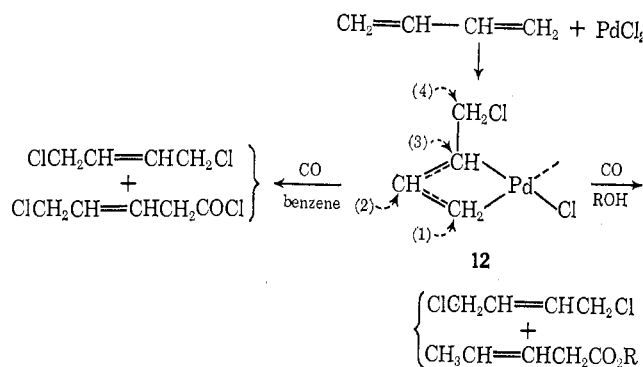
(34) Recently,  $\pi$ -allylic complex formation from simple olefins under mild conditions has been reported: A. D. Ketley and J. Braatz, *Chem. Commun.*, 169 (1968).

(35) S. Imamura and J. Tsuji, 21st Meeting of the Japan Chemical Society, Osaka, 1968, p 1998.

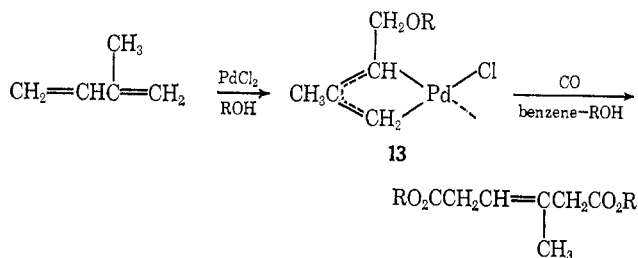


This reaction exemplifies combination of two principal properties of Pd(II), namely carbonylation and abstraction of hydrogens *via*  $\pi$ -allyl complex formation.

Conjugated dienes form  $\pi$ -allylic complexes when treated with PdCl<sub>2</sub>. The allylic complex formed from butadiene is a chloromethyl-substituted  $\pi$ -allylpalladium chloride (*e.g.*, **12**). There are two possible sites of CO attack in such diene complexes (C<sub>1</sub>, C<sub>4</sub>). Monocarbonylation of the butadiene complex **12** in ethanol or benzene gives the following products.<sup>36</sup>



Carbonylation of isoprene complex **13**, which has an ethoxy group instead of the chlorine at C<sub>4</sub>, gave 3-methyl-3-hexenedioate as a dicarbonylation product, accompanied by other products.<sup>37</sup>



In addition, carbonylation of dienes can be carried out catalytically, giving different  $\beta$ , $\gamma$ -unsaturated esters. When butadiene is carbonylated in alcohol containing HCl in the presence of a catalytic amount of PdCl<sub>2</sub>, the product is 3-pentenoate.<sup>36,38</sup> Isoprene gives 4-methyl-3-pentenoate as the main product.<sup>39</sup>

(36) J. Tsuji, J. Kiji, and S. Hosaka, *Tetrahedron Letters*, 605 (1964).

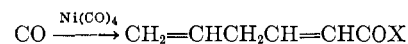
(37) J. Tsuji and S. Hosaka, *J. Am. Chem. Soc.*, **87**, 4075 (1965).

(38) S. Brewis and P. R. Hughes, *Chem. Commun.*, 157 (1965).

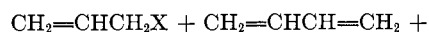
(39) J. Tsuji and S. Hosaka, unpublished results.

Carbonylation of allene through  $\pi$ -allylic complexes is also possible.<sup>40,41</sup>

Here it is worthwhile to point out the difference between palladium- and nickel-catalyzed carbonylation of allyl chloride. Both palladium and nickel carbonyl catalyze the simple allylic carbonylation, giving 3-butenolate. In addition, nickel carbonyl catalyzes the selective addition of allyl halide, acetylene, and CO to give 2,5-hexadienoate.<sup>42</sup> On the other hand,

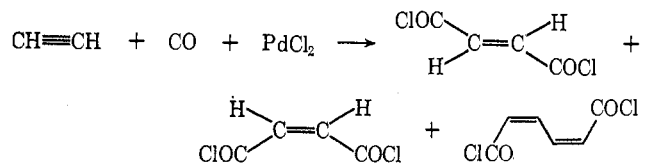


in the palladium-catalyzed reactions, allyl chloride reacts with butadiene (but not with acetylene) and CO to form 3,7-octadienyl chloride, although the reaction is not selective.<sup>31</sup>

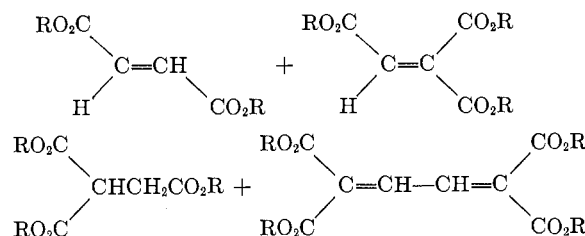
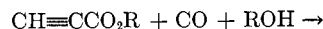


**Carbonylation of Acetylenes.** Both PdCl<sub>2</sub> and metallic palladium are known to be active for cyclization or oligomerization of acetylenic compounds.<sup>43</sup> Acetylenic compounds, like olefins, can be carbonylated by the catalytic action of palladium without forming cyclized products. A specific feature of the palladium-catalyzed carbonylation of acetylenic bonds is the occurrence of extensive dicarbonylation rather than monocarbonylation.

Acetylene is carbonylated by the catalytic action of PdCl<sub>2</sub> in alcohol containing iodine to give several unsaturated esters.<sup>44</sup> When carbonylation is carried out in benzene in the presence of PdCl<sub>2</sub> under pressure, fumaryl, maleyl, and muconyl chlorides are obtained.<sup>45</sup> Chiusoli found that a similar reaction may be realized at room temperature by passing acetylene and CO into methanol containing PdCl<sub>2</sub> and thiourea.<sup>46</sup>



Carbonylation of acetylenemonocarboxylate, carried out in the presence of PdCl<sub>2</sub> and HCl in alcohol, gives the following products.<sup>47</sup>



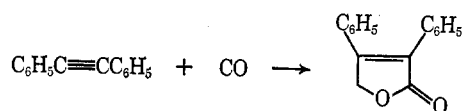
(40) J. Tsuji and T. Susuki, *Tetrahedron Letters*, 3027 (1965).

(41) T. Susuki and J. Tsuji, *Bull. Chem. Soc. Japan*, **41**, 1954 (1968).

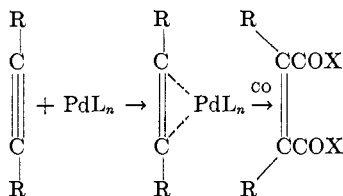
(42) G. P. Chiusoli and L. Cassar, *Angew. Chem. Intern. Ed. Engl.*, **6**, 124 (1967), and the literature cited therein.

Acetylenedicarboxylate is also carbonylated smoothly at room temperature to give ethanetetra-carboxylate as a main product (50%) and ethene- and ethanetri-carboxylates as minor products (25%).

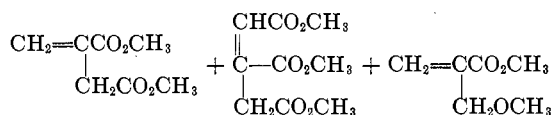
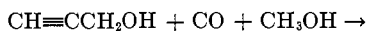
Diphenylacetylene is carbonylated smoothly without cyclization, and the main product is diphenylcrotonolactone (60%).<sup>48</sup> The lactone is certainly formed by simultaneous *cis* attack of 2 mol of CO on the triple bond, followed by reduction of one of the carbonyl functions.



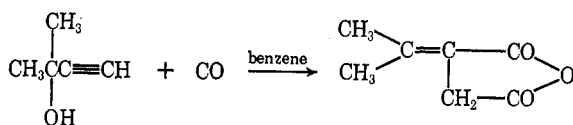
Although the mechanism of the palladium-catalyzed carbonylation of acetylenic compounds is not clear at present, it is highly probable that the complex shown below is an intermediate of the *cis*-dicarbonylation of acetylenic bonds. Noble metal complex formation of this type has recently been reported.<sup>49, 50</sup>



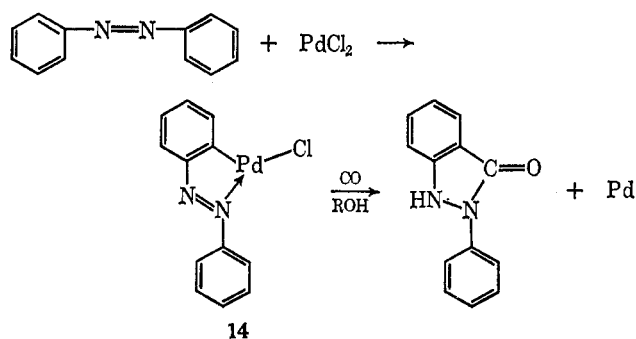
The carbonylation of propargyl alcohol was carried out in the presence of palladium catalyst in methanol containing HCl at 100°. <sup>51</sup> Methyl 2-(methoxymethyl)-acrylate (minor), methyl itaconate, and methyl acrylate were the products. 2-Methyl-3-butyn-2-ol in



methanol is attacked by 1 or 2 mol of CO, giving methyl 4-methoxy-4-methyl-2-pentenoate, itaconate, (1-methoxy-1-methylethyl)maleate, and terebate. In benzene in the presence of PdCl<sub>2</sub>, itaconic anhydride is obtained selectively in 42% yield.



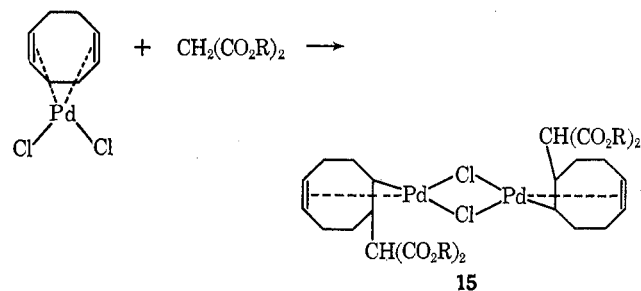
**Carbonylation of Aromatic Compounds.** PdCl<sub>2</sub> and azobenzene readily form, by aromatic substitution, a stable complex (14).<sup>52</sup> The complex is interesting for further studies by virtue of its reactive palladium-carbon  $\sigma$  bond. The complex reacts with CO in alcohol at 50° under pressure, and 2-phenyl-3-indazolinone is obtained in high yield.<sup>53</sup>



Henry found that arylpalladium salts prepared *in situ* from arylmercuric salts and various palladium compounds react with CO in hydroxylic solvents to form arylcarboxylic acids or their derivatives.<sup>54</sup>

### Reactions of Olefins and $\pi$ -Allylic Complexes with Carbanions

We have investigated the possibility of carbon-carbon bond formation by reaction of olefin complexes with carbanions, and have found that malonate or acetoacetate reacts smoothly with 1,5-cyclooctadiene-palladium chloride complex at room temperature.<sup>55, 56</sup> A new complex (15) which has a new carbon-carbon bond was isolated in quantitative yield. The new



complex still has  $\pi$  and  $\sigma$  bonds with palladium and undergoes further transformations on treatment with various bases. When a strong base is used, a bicyclo-[6.1.0]nonene derivative (16) is formed with precipitation of Pd. When another molecule of malonate is allowed to react with the complex, attack occurs intermolecularly at the  $\pi$ -complexed olefinic bond and is followed by a transannular reaction of the eight-membered ring to form a bicyclo[3.3.0]octane ring system (17) containing two malonate moieties.

$\pi$ -Allylpalladium chloride reacts with ethyl malonate

(52) A. C. Cope and R. W. Siekman, *J. Am. Chem. Soc.*, **87**, 3272 (1965).

(53) H. Takahashi and J. Tsuji, *J. Organometal. Chem.*, **10**, 511 (1967).

(54) P. M. Henry, *Tetrahedron Letters*, 2285 (1968).

(55) J. Tsuji and H. Takahashi, *J. Am. Chem. Soc.*, **87**, 3275 (1965).

(56) H. Takahashi and J. Tsuji, *ibid.*, **90**, 2387 (1968).

(43) For a review see: P. M. Maitlis, *Advan. Organometal. Chem.*, **4**, 95 (1966).

(44) G. Jacobsen and H. Späthe, German Patent, 1138760 (1962), *Chem. Abstr.*, **58**, 6699 (1963).

(45) J. Tsuji, M. Morikawa, and N. Iwamoto, *J. Am. Chem. Soc.*, **86**, 2095 (1964).

(46) G. P. Chiusoli, C. Venturello, and S. Merzoni, *Chem. Ind. (London)*, 977 (1968).

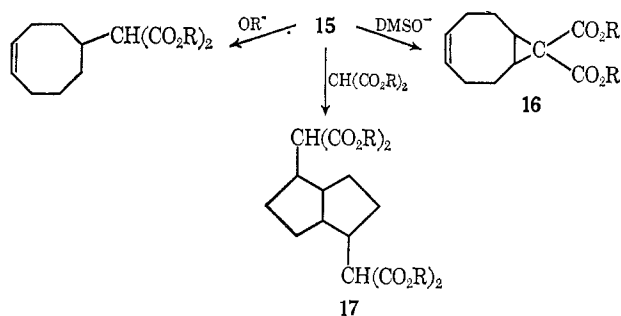
(47) J. Tsuji and T. Nogi, *J. Org. Chem.*, **31**, 2641 (1966)

(48) J. Tsuji and T. Nogi, *J. Am. Chem. Soc.*, **88**, 1289 (1966).

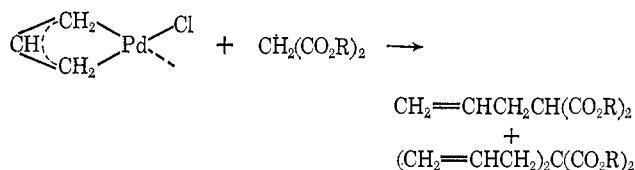
(49) J. P. Collman and J. W. Kang, *ibid.*, **89**, 844 (1967).

(50) E. O. Greaves and P. M. Maitlis, *J. Organometal. Chem.*, **6**, 104 (1966).

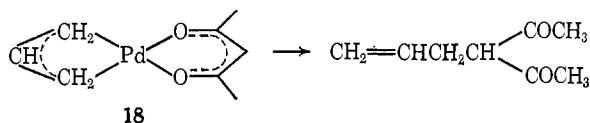
(51) J. Tsuji and T. Nogi, *Tetrahedron Letters*, 1801 (1966).



to give allyl- and diallylmalonates.<sup>57, 58</sup> It is probable that malonate anion at first coordinates to palladium and that coupling between the coordinated malonate and allyl groups then takes place. As supporting



evidence, we found that thermal decomposition of  $\pi$ -allylacetylacetonate (18) gave allylacetylacetonone by ligand coupling. The same coupling reaction proceeds by the action of  $CO$ .<sup>59</sup>



In another example, the morpholine enamine of cyclohexanone reacts with  $\pi$ -allylpalladium chloride to introduce the allyl group into the  $\alpha$  position of cyclohexanone, forming 2-allylcyclohexanone.

These reactions of  $\pi$ -olefin and  $\pi$ -allyl complexes with nucleophiles show that they differ from reactions of the commonly used organometallic compounds. For example, carbon-carbon bond formation takes place by using  $Mg(0)$  or  $Zn(0)$ . The first step of the Grignard or Reformatsky reaction is irreversible oxidative addition ( $Mg(0) \rightarrow Mg(II)$ ) of alkyl halides to these metals. With these reagents, carbon-carbon bond formation takes place by attack of electrophiles such as carbonyl compounds on the carbon-metal bond. On the other hand, with palladium complexes, nucleophiles attack the palladium-carbon bond. This is due to the fact that divalent  $Mg$  tends to make the carbon quite anionic, whereas  $Pd(II)$  is easily reduced to the zerovalent state by abstracting two electrons.

The differences between  $\pi$ -allyl complexes of palladium and nickel are also noteworthy.  $\pi$ -Allylnickel halide reacts with electrophiles such as carbonyl compounds, alkyl halides, and acrylonitrile.<sup>42, 60, 61</sup> Fur-

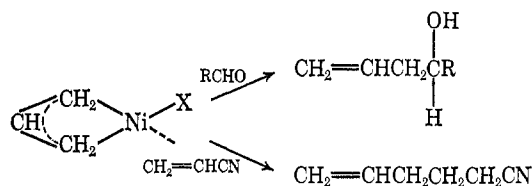
(57) J. Tsuji, H. Takahashi, and M. Morikawa, *Tetrahedron Letters*, 4387 (1965).

(58) J. Tsuji, H. Takahashi, and M. Morikawa, *Kogyo Kagaku Zasshi*, **69**, 920 (1966).

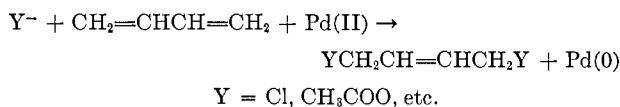
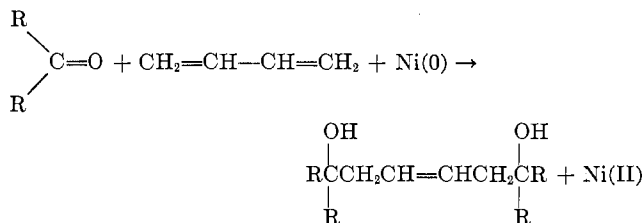
(59) Y. Takahashi, S. Sakai, and Y. Ishii, *Chem. Commun.*, 1092 (1967).

(60) M. Dubini, F. Montino, and G. P. Chiusoli, *Chim. Ind. (Milan)*, **49**, 839 (1965).

(61) E. J. Corey and M. F. Semmelhack, *J. Am. Chem. Soc.*, **89**, 2755 (1967).



thermore, butadiene reacts with carbonyl compounds in the presence of  $Ni(0)$  to give a 1,6-dihydroxy-3-hexene derivative,<sup>62</sup> whereas  $Pd(II)$  reacts with butadiene to give 2-butene derivatives substituted with nucleophiles at the 1 and 4 positions.

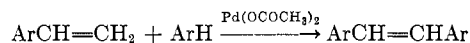


### Oxidative Coupling of Aromatic and Olefinic Compounds

Carbon-carbon bond formation is possible by oxidative coupling of olefinic and aromatic compounds. For example, vinyl acetate is dimerized to give 1,4-diacetoxybutadiene as a main product when oxidized with palladium acetate.<sup>63</sup> Also, several substituted olefins can be oxidatively dimerized by  $Pd(II)$  to give substituted butadienes in high yield.<sup>64</sup> Furthermore,



palladium acetate catalyzes reaction of styrene with benzene to form stilbene in high yield.<sup>65, 66</sup>



Although the mechanism of these oxidative couplings seems to be complex, it is certain that some sort of benzene-palladium  $\sigma$ -bond formation takes place during the reactions. As supporting evidence, the  $N,N$ -dimethylbenzylamine-palladium complex, which has a palladium-carbon bond, reacts with styrene in acetic acid at room temperature to give stilbene derivatives easily.<sup>67</sup>

Ingenious synthetic reactions involving palladium-aryl  $\sigma$  bonds have been reported by Heck.<sup>68</sup> Aryl-palladium salts, presumably generated *in situ* from

(62) G. Wilke, Plenary Lecture given at the 10th International Conference on Coordination Chemistry, Tokyo, Sept 1967.

(63) C. F. Kohll and R. van Helden, *Rec. Trav. Chim.*, **86**, 193 (1967).

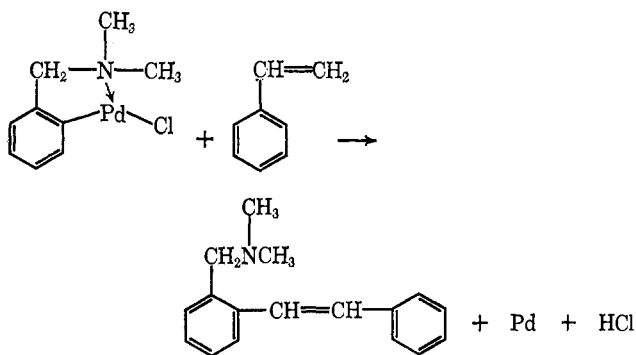
(64) H. C. Volger, *ibid.*, **86**, 677 (1967).

(65) I. Moritani and Y. Fujiwara, *Tetrahedron Letters*, 1119 (1967).

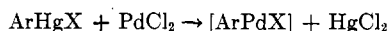
(66) Y. Fujiwara, I. Moritani, M. Matsuda, and S. Teranishi, *ibid.*, 633, 3863 (1968).

(67) J. Tsuji and K. Ohno, unpublished results.

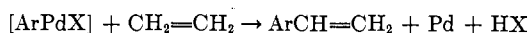
(68) R. F. Heck, private communication.



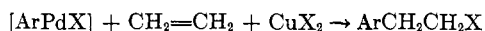
arylmethylmercury salts and palladium salts, but not isolated, react with various olefinic compounds. An example



is reaction with olefins to form styrene derivatives.<sup>69</sup>

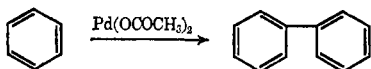


Also, reaction with ethylene in the presence of cupric halides and a catalytic amount of palladium salt forms a 2-haloethylbenzene.<sup>70</sup> Reaction with conjugated

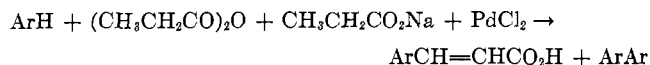


diene gives arylbutenyl acetate.<sup>71</sup> Also reactions of arylpalladium salts with allylic alcohols,<sup>72</sup> allylic halides,<sup>73</sup> and aldehyde enol esters<sup>74</sup> have been carried out, giving various interesting products.

Quite remarkably, it was found that benzene itself can be coupled in the presence of Pd(II) in acetic acid-sodium acetate to yield biphenyl.<sup>75</sup> In the



absence of sodium acetate, no coupling takes place. Davidson reported that this reaction proceeds *via* the formation of a very unstable phenylpalladium complex.<sup>76,77</sup> Benzoic acid (as well as biphenyl) is formed by the reaction of benzene with acetic anhydride, sodium acetate, and PdCl<sub>2</sub>, although the yield is not high (*ca.* 20%). With propionic anhydride, cinnamic acid is formed.<sup>78</sup>



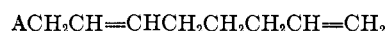
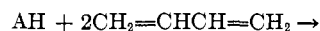
The mechanisms of the reactions shown above involving Pd(II) and benzene are apparently complex; further studies are necessary.

### Hydrogen Shift Reactions

Another reaction catalyzed by palladium is carbon-carbon bond formation *via* intermolecular hydrogen shift. Simple olefins such as ethylene can be dimerized

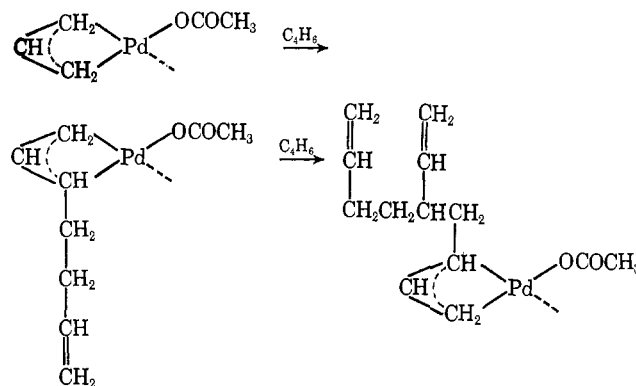
in the presence of a catalytic amount of PdCl<sub>2</sub> to give a mixture of butenes.<sup>79,80</sup> In this dimerization, the selection of solvents is important, as is frequently the case in transition metal catalyzed reactions.<sup>81</sup>

The most interesting example of carbon-carbon bond formation with an intermolecular hydrogen shift is observed in the dimerization of butadiene to give 1,3,7-octatriene.<sup>82</sup> Furthermore, the dimerization of butadiene takes place with incorporation of nucleophiles such as phenol, alcohols, amines, and carboxylic acids. These are incorporated mainly at the terminal position to form substituted octadienes, in the presence of Pd(0) complex<sup>82,83,84</sup> or Pd(II) complex + sodium phenoxide.<sup>85,86</sup> 1,3,7-Octatriene



reacts with butadiene in the presence of nucleophiles to give terminally substituted dodecatrienes.<sup>86</sup> These reactions certainly proceed through  $\pi$ -allylic complexes, and the nucleophiles attack the intermediate  $\pi$ -allylic complexes. Studies with deuterium-labeled compounds showed that hydrogen from nucleophiles migrates to C-6 of the octadiene.<sup>84</sup>

As a somewhat related reaction,  $\pi$ -allylpalladium complexes react with butadiene to form new  $\pi$ -allyl complexes *via* addition of the allyl group to the diene.<sup>31,59</sup> Furthermore, stepwise addition of butadiene to  $\pi$ -allyl complex to form oligomers has been



(76) J. M. Davidson and C. Trigg, *Chem. Ind.* (London), 457 (1966).

(77) J. M. Davidson and C. Trigg, *J. Chem. Soc.*, 1324 (1968).

(78) S. Nishimura, T. Sakakibara, and Y. Odaira, Symposium on Organometallic Chemistry, Tokyo, Japan, Oct 1968.

(79) J. T. van Gemert and P. R. Wilkinson, *J. Phys. Chem.*, **68**, 645 (1964).

(80) Y. Kusunoki, R. Tatsuno, and S. Tsutsumi, *Bull. Chem. Soc. Japan*, **39**, 2021 (1966).

(81) A. D. Ketley, L. P. Fischer, A. J. Berlin, C. R. Morgan, E. H. German, and T. R. Steadman, *Inorg. Chem.*, **6**, 657 (1967).

(82) S. Takahashi, T. Shibano, and N. Hagihara, *Tetrahedron Letters*, 2451 (1967).

(83) S. Takahashi, T. Shibano, and N. Hagihara, *Bull. Chem. Soc. Japan*, **41**, 454 (1968).

(84) S. Takahashi, S. Yamazaki, and N. Hagihara, *ibid.*, **41**, 254 (1968).

(85) E. J. Smutny, *J. Am. Chem. Soc.*, **89**, 6793 (1967).

(86) E. J. Smutny, 11th International Conference on Coordination Chemistry, 1968, Tel-Aviv, Israel, and private communication.

(69) R. F. Heck, *J. Am. Chem. Soc.*, **90**, 5518 (1968).

(70) R. F. Heck, *ibid.*, **90**, 5538 (1968).

(71) R. F. Heck, *ibid.*, **90**, 5542 (1968).

(72) R. F. Heck, *ibid.*, **90**, 5526 (1968).

(73) R. F. Heck, *ibid.*, **90**, 5531 (1968).

(74) R. F. Heck, *ibid.*, **90**, 5535 (1968).

(75) R. van Helden and C. Verberg, *Rec. Trav. Chim.*, **84**, 1263 (1965).



carried out and the intermediate complexes have been isolated.<sup>31</sup>

### Concluding Remarks

On the preceding pages, major examples of carbon-carbon bond formation involving palladium compounds are described. Most of these reactions are special for palladium and difficult to attain with other methods. One advantage of these reactions is the ease of handling palladium, which is stable and can be handled without rigorous exclusion of air. Some reactions consume a stoichiometric amount of Pd(II), but it can be recovered easily and reoxidized. In some cases, *in situ* reoxidation of Pd(0) is possible by selecting the reaction conditions, as in the Wacker process.

In the palladium-catalyzed reactions, the role of the auxiliary ligands in the catalytic species is critically important. Profound changes of the course, products, and yield of reactions are caused by changing the ligands. For example, the reactivities of palladium

acetate, halides, and nitrate are quite different. Also marked effects of phosphine ligands are observed in some palladium-catalyzed reactions. Another important factor to be considered is the solvent. Various solvents coordinate and stabilize palladium catalysts in various degrees and accelerate or retard reactions. Careful selection of these factors is very important.

The mechanisms of the carbon-carbon bond formation reactions are almost wholly unexplored. Much has to be done before we can understand the nature of the interaction between palladium and various unsaturated compounds, especially aromatic compounds.

*I am grateful to Professor J. P. Collman, Dr. H. G. Tennent, and Dr. R. F. Heck for their careful reading of the manuscript and for suggestions. Stimulating discussion with Dr. E. J. Smutny and the cooperation of Dr. R. van Helden in making available his unpublished results are gratefully acknowledged. I also express my appreciation to my coworkers who have contributed to the work described in this paper.*

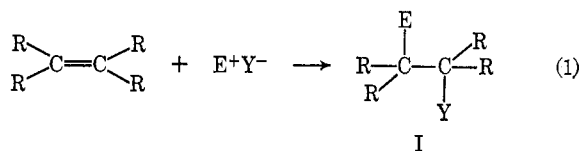
## Electrophilic Additions to Strained Olefins

T. G. TRAYLOR

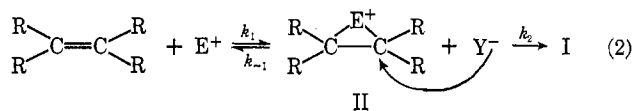
Department of Chemistry, University of California, San Diego, Revelle College, La Jolla, California

Received August 19, 1968

The additions of electrophilic reagents such as chlorine, bromine, sulfenyl halides, mercuric salts, and protic acids to simple cyclic and acyclic olefins usually occur with *trans* stereochemistry.<sup>1,2</sup>



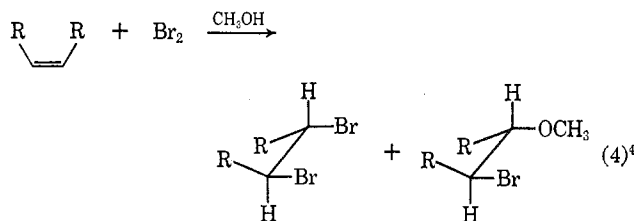
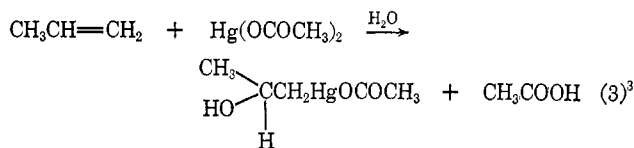
In those cases where high stereospecificity is observed, the *trans* addition is generally attributed to the formation of a strong olefin-electrophile complex which behaves as a three-membered ring. This ring intermediate presumably opens by nucleophilic attack with inversion of configuration (S<sub>N</sub>2) at the carbon where positive charge would be most stabilized (Markovnikov addition). The examples in reactions 3 and 4



(1) Electrophilic additions to olefins and acetylenes have been reviewed recently.<sup>2</sup> The reader is referred to ref 2a for discussions of various mechanisms of addition.

(2) (a) R. C. Fahey in "Topics in Stereochemistry," N. Allinger and E. L. Eliel, Ed., John Wiley & Sons, Inc., New York, N. Y., in press; (b) P. B. D. de la Mare and R. Bolton, "Electrophilic Additions to Unsaturated Systems," Elsevier Publishing Co., New York, N. Y., 1966.

exemplify some of the results which characterize electrophilic additions.



If the olefin-electrophile complex is rapidly and reversibly formed, as is often assumed, then the transition state for the addition has structure III. While there is general agreement that the *trans*-coplanar transition state, III, for electrophilic addition is lower in energy than the corresponding *cis* transition state, IV, there is no such agreement that III is always pre-

(3) (a) F. C. Whitmore, "Organic Compounds of Mercury," Chemical Catalog Co., Reinhold Publishing Corp., New York, N. Y., 1921; (b) W. Kitching, *Organometal. Rev.*, **3**, 61 (1968); (c) N. S. Zefirov, *Russ. Chem. Rev.*, **34**, 527 (1965).

(4) Reference 2a, pp 286-288.