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Isotope Effect of Aromatic Coupling Reaction Catalyzed by Palladium Acetate

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Isotope effect in palladium catalyzed coupling reaction of aromatic compounds has been measured under oxygen pressure as well as under atmospheric pressure. For deuterobenzene, a large isotope effect (k_H/k_D) was found to be 2.1–2.5 at 150°C under oxygen pressure and to be 4.1–5.1 at room temperature under atmospheric pressure. On the basis of these isotope effects, we proposed the two-step hydrogen abstraction mechanism. Under oxygen pressure, oxygen plays an important role in the re-oxidation of reduced palladium(O) complex.

INTRODUCTION

Since R. van Helden first reported (*1*), the coupling reaction of aromatic compounds using palladium salts has been studied extensively by many workers (*2–5*) in order to obtain some insights into the mechanism of the oxidative coupling. Under the conditions used, however, the reaction has not proceeded catalytically. The yields of products were less than 100% based on palladium salt since Pd metal precipitated during the reaction.

In the study of the coupling reaction of benzene and benzene-d_6 under the atmospheric oxygen in acetic acid, Davidson (*6*) measured the rate constant in the system by means of ultraviolet spectrometry. The remarkable kinetic isotope effect (k_H/k_D = 5.0) was observed at the step of the formation of phenyl-palladium(II) complex. In addition, the competitive arylation of styrene with benzene and benzene-d_6 gave stilbene where the ratio of stilbene/stilbene-d_5 was measured by mass spectrometry to be 5.3 (*7*).

In this paper, we present the effect of the oxygen partial pressure as well as the catalyst concentration concerning the yields in palladium catalyzed coupling reaction of toluene under oxygen pressure. There was also observed primary kinetic isotope effect in the following systems. (a) benzene–benzene-d_6 system; (b) benzene–benzene-d_6–toluene system; (c) benzene–benzene-d_6–*p*-xylene system.

From the results, we have speculated the reaction scheme on the basis of the re-oxidation of reduced palladium.

EXPERIMENTAL

Benzene, toluene, and *p*-xylene were of reagent grade and rectified before use. Benzene-d_6 (99% purity) purchased from Merck Co. Ltd. was used without further purification. Palladium acetate was prepared from palladium chloride according to the procedure reported (*8*). The reaction products identified in the previous paper (*5, 9*) were analyzed quantitatively by GLC (Shimadzu-4APT) with helium as carrier gas, using either 1-m long column A packed with SE-30 on Diasolid-L or 2-m long column B with Versamid 900 on Diasolid-L For the determination of yields and mole fractions of products, the following interna standards were used; dibenzyl for bipheny and bitolyl; *trans*-stilbene for methyl bi phenyl, 2,5-dimethyl biphenyl, and bixylyl respectively. The percent compositions o isomers containing D-atom was determined by mass spectrometer (Hitachi RMU-6 under chamber voltage of 15 V.

The Reactions of Toluene with Palladium Acetate

A series of experiments was run, where (1) the amount of palladium acetate was maintained constant at 0.5 mmole and the pressure of the gaseous mixture (the molar ratio of oxygen and nitrogen 1 : 1) was varied from 6 to 75 kg/cm^2 and subsequently (2) the pressure was maintained constant at 50 kg/cm^2 and the concentration of palladium acetate was varied from 0.08 to 2.67 mmole.

Case 1. Palladium acetate (0.112 g) and toluene (50 ml) were weighed into the 250-ml glass vessel which was inserted in the stainless steel autoclave. The autoclave was heated at 120°C for 4 hr under the appropriate pressure. After GLC analysis (column B at 180°C), the result is shown in Fig. 1.

Case 2. The same procedure as in Case 1 was followed except of 150°C for 6 hr under the pressure of 50 kg/cm^2, the appropriate amount of palladium acetate, and the equimolar amount of acetylacetone. The result is shown in Fig. 2.

The Competitive Reactions of Aromatic Compounds with Pd(OAc)$_2$

Case of benzene and benzene-d_6. The glass vessel containing palladium acetate (0.0336 g), benzene (10 ml), benzene-d_6 (10 ml), and acetylacetone (0.020 g) was inserted into the 100 ml autoclave which was heated at 150°C for 6 hr under the pressure of 50 kg/cm^2 (O_2:N_2 = 1:1). Biphenyl (0.804 g) formed was identified by GLC with column A at 150°C.

Case of benzene, benzene-d_6, and toluene. The procedure was followed in the same way as the above case, charging palladium acetate (0.0336 g), benzene (5 ml) benzene-d_6 (5 ml), toluene (10 ml), and acetylacetone (0.020 g). After reaction, GLC analysis (column B at 180°C) showed biphenyl (0.297 g), methyl biphenyl (0.640 g), and bitolyl (0.270 g), as reaction products.

Case of benzene, benzene-d_6, and p-xylene. The similar reaction used p-xylene instead of toluene was carried out, giving biphenyl (0.397 g), 2,5-dimethyl biphenyl (0.339 g), and bixylyl (0.042 g) (column B at 180°C).

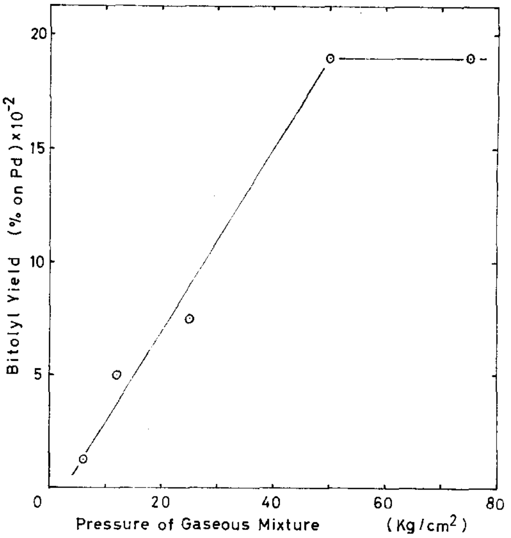


FIG. 1. Effect of reaction pressure on bitolyl yield. Toluene 50 ml; palladium acetate 0.112 g at 120°C for 4 hr.

The Competitive Reaction Catalyzed by Palladium Acetate through an Organomercury Compound

Mercuric acetate (3.2 g) was added at room temperature to the mixture of toluene

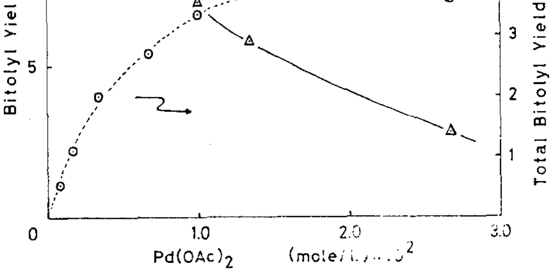


FIG. 2. Effect of palladium acetate concentration on bitolyl yield. Toluene 50 ml, acetylacetone equimolar to Pd(OAc)$_2$ at 150°C for 6 hr under 50 kg/cm^2 of the gaseous mixture (N_2:O_2 = 1:1). —○— bitolyl yield (% on Pd), ...△... total bitolyl yield (mmole).

(10 ml) and acetic acid (6 ml). On addition of $HClO_4$ (1.25 ml), the mercuration was completed in 15 min. To this solution was added the mixture of palladium acetate (1.1 g), benzene (5 ml), benzene-d_6 (5 ml), and acetic acid (5 ml). After 90 min, the reaction mixture was filtered, washed, and dried. GLC analysis with column B at 180°C showed biphenyl (0.062 g), methyl biphenyl (0.062 g), and bitolyl (0.316 g) as reaction products.

On the other hand, a mixture of mercuric acetate (3.2 g), benzene (5 ml), benzene-d_6 (5 ml), perchloric acid (1.25 ml), and acetic acid (6 ml) was stirred vigorously at room temperature for 15 min, and subsequently to this solution, 5 ml of acetic acid containing palladium acetate (1.1 g) was added. The solution was stirred vigorously for 90 min. GLC analysis (column A at 150°C) showed biphenyl (0.273 g).

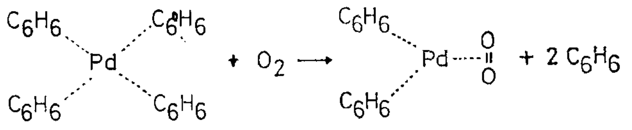
RESULTS AND DISCUSSION

The Effect of the Oxygen Partial Pressure

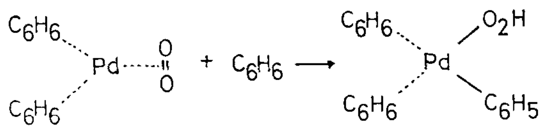
In order to examine the dependence of the yields of bitolyl against the oxygen partial pressure (P_{O_2}), the experiments were carried out under the several P_{O_2} of 3, 6, 12, 25, and 37.5 kg/cm². The yields of bitolyl are plotted against the corresponding P_{O_2}, as shown in Fig. 1.

The yields of bitolyl are increased proportionally with increasing oxygen partial pressure in the range of 3–25 kg/cm². However, the yields remain constant as the oxygen partial pressure exceeds 25 kg/cm². This result may imply that the coupling reaction is dependent upon the diffusion of oxygen under P_{O_2} of 3–25 kg/cm², but upon the formation of arylpalladium(II) complex under higher than 25 kg/cm² of P_{O_2}.

As shown in Fig. 1, bitolyl is produced in 1800% yield based on Pd salt, indicating that the oxidation–reduction reactions of reduced palladium take place at least 18 times since the yields of bitolyl have not exceeded 100% based on Pd salt used under the atmospheric oxygen pressure.* Under oxygen pressure, hence, the reaction of reduced Pd with molecular oxygen may take place smoothly in toluene or benzene solution to give the oxygen coordinated Pd(O) complex. Recently, it is known that molecular oxygen reacts with Pd(O) and Ni(O) complexes to form oxygen–metal complex (*10*). Interestingly, the coordinated oxygen (*11*) serves to be an oxygenative reagent to convert pi-coordinating ligand around metal into the corresponding oxide. If aromatic compound having electron donative character is presumed to behave in a similar way as triphenylphosphine (*12*), the re-oxidation of Pd(O) complex to Pd(II) can be represented as follows;



(1)



(2)

the conversion of pi-bonding on metal to sigma-bonding has been discussed in the transition metal catalysis (*13*).

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* When the same coupling reaction is carried out under an atmospheric oxygen pressure, the yield of bitolyl is only 16% based on Pd salt charged.

The Effect of the Catalyst Concentration

Varying the concentration of palladium acetate, the coupling reaction of toluene was carried out in the presence of acetylacetone equimolar to palladium acetate under oxygen pressure. In Fig. 2, the overall yields and the yields based on Pd salt used are plotted against the concentrations of palladium acetate.

The overall yields of bitolyl increase with increasing the catalyst concentrations until palladium diacetate reaches at 1.4×10^{-2} mole/liter. When 2.7×10^{-2} mole/liter of catalyst is applied, however, the yields of bitolyl increase not at all. On the other hand, the yields based on Pd salt charged decrease markedly as the catalyst concentrations increase higher than 2.0×10^{-3} mole/liter. This result indicates that in the high catalyst concentration, all of Pd(O) complex formed are not completely regenerated as in the Eqs. (1 and 2). The deactivation of Pd(O) complex may take account for the shortage of oxygen to contact with Pd(O) complex which coagulates each other to palladium black precipitated.

Primary Kinetic Isotope Effect

Davidson and Triggs (*6*) have reported the oxidative coupling reaction of benzene and benzene-d_6, finding primary kinetic isotope effect ($k_H/k_D = 5.3$) at 50°C under the atmospheric oxygen pressure in acetic acid solution. Independently, Shue (*7*) has reported the competitive coupling reaction of styrene with benzene and benzene-d_6, observing primary kinetic isotope effect ($k_H/k_D = 5.3$) at 80°C. The coupling reaction of benzene with styrene and styrene-β,β-d_2, however, gave small kinetic isotope effect of 1.25. These results led the conclusion that the formation of sigma-arylpalladium bonding is the rate-determining step in the coupling reaction under the atmospheric oxygen pressure.

In the present study of the palladium catalyzed coupling reaction of benzene-d_6 with other aromatic compounds under oxygen pressure, there was found the remarkable difference on the ratios of the coupling products between benzene and benzene-d_6 as seen in Table 1. In addition, ratios of biphenyl isomers are also dependent upon reaction temperature as seen in Fig. 3 where the kinetic isotope effect decreases along with increasing reaction temperature.

Now, it should be noticed that all of products obtained in three systems undergo the exchange on the benzene nucleus between H and D atoms.† Accordingly, the isomers listed in Table 1 are followed by the correction of H–D Mixing.

The oxidative coupling reaction of benzene had been postulated to proceed according to the following reaction scheme (*2*).

$$\mathrm{Pd(AcO)_2 + C_6H_6 \longrightarrow C_6H_5\text{-}Pd(AcO) + AcOH} \quad (3)$$

$$\mathrm{C_6H_5\text{-}Pd(AcO) + C_6H_6 \longrightarrow C_6H_6\text{-}Pd\text{-}C_6H_5 + AcOH} \quad (4)$$

$$\mathrm{C_6H_5\text{-}Pd\text{-}C_6H_5 \xrightarrow{fast} C_6H_5\text{-}C_6H_5 + Pd(O)} \quad (5)$$

In this case, the yields of biphenyl are less than 100% based on Pd salt charged since

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† It may be considered that the products based on exchanging hydrogen for deuterium atom are produced by the following equilibrium scheme.

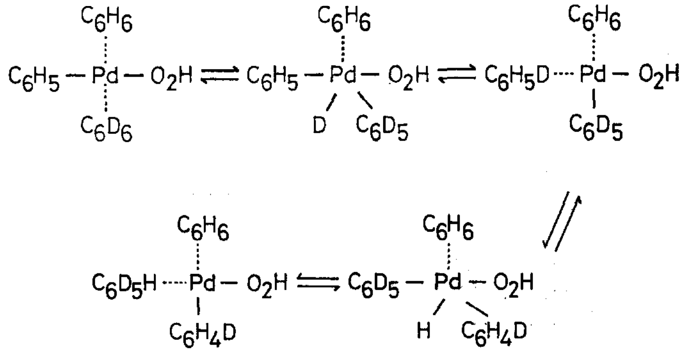

TABLE 1

COMPETITIVE COUPLING OF AROMATIC COMPOUNDS WITH PALLADIUM ACETATE (0.15 mmole) IN THE PRESENCE OF ACETYLACETONE (0.20 mmole) AT 150°C FOR 6 HR UNDER 50 kg/cm^2 OF GASEOUS MIXTURE (N_2:O_2 = 1:1)

(a) benzene (10 ml), benzene-d_6 (10 ml)
(b) benzene (5 ml), benzene-d_6 (5 ml), and toluene (10 ml)
(c) benzene (5 ml), benzene-d_6 (5 ml), and *p*-xylene (10 ml)

System	Product	Yield (mM)	Ratio of isomer	
a	Biphenyl	5.12	B-B/B-B-d_{10}	5.15
			B-B-d_5/B-B-d_{10}	4.31
b	Biphenyl	1.89	B-B/B-B-d_{10}	4.84
			B-B-d_5/B-B-d_{10}	4.10
	Methyl-Biphenyl	3.79	T-B/T-B-d_5	2.36
	Bitolyl	1.49	—	—
c	Biphenyl	2.52	B-B/B-B-d_{10}	5.35
			B-B-d_5/B-B-d_{10}	4.61
	2,5-Dimethylbiphenyl	1.85	X-B/X-B-d_5	2.19
	Bixylyl	0.20	—	—
	Mean value		B-B/B-B-d_{10}	5.11
			B-B-d_5/B-B-d_{10}	4.34

reduced palladium is not followed by the re-oxidation with molecular oxygen.

Under oxygen pressure, however, there was the induction period of ca. 20 min. at the early stage of the reaction, indicating that palladium acetate converts into more active Pd-species. Pd(O) complex formed may be re-oxidized with oxygen to Pd(II) complex according to the equation (1) and (2), and thus the reaction can be cycled as follows;

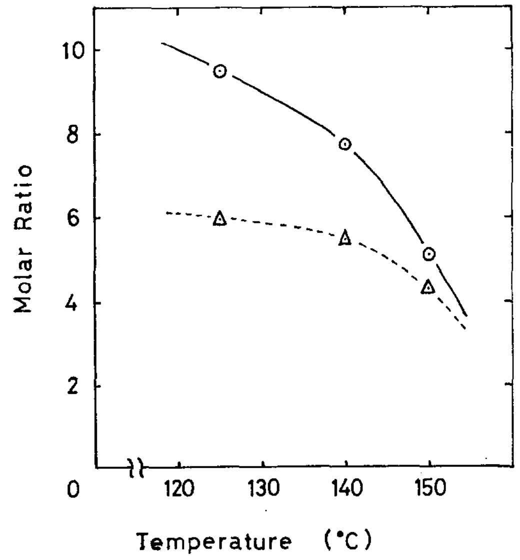

FIG. 3. Temperature dependence of isotope effect. The conditions are shown in Table 1(a). —⊙— biphenyl/biphenyl-d_{10}, ...△... biphenyl-d_5/ biphenyl-d_{10}.

$$\mathrm{Pd(O)\cdots O_2 + C_6H_6 \longrightarrow C_6H_5\text{-}Pd(II)\text{-}OOH} \quad (6)$$

$$\mathrm{C_6H_5\text{-}Pd(II)\text{-}OOH + C_6H_6 \longrightarrow C_6H_5\text{-}Pd(II)\text{-}C_6H_5 + H_2O_2} \quad (7)$$

$$\mathrm{C_6H_5\text{-}Pd(II)\text{-}C_6H_5 \xrightarrow{fast} C_6H_5\text{-}C_6H_5 + Pd(O)} \quad (5)$$

$$\mathrm{Pd(O) + O_2 \rightleftarrows Pd(O)\cdots O_2} \quad (1)$$

It is possible to observe primary kinetic isotope effect at both steps of (6) and (7) in the competitive coupling reaction of benzene and benzene-d_6. Two reactions may take place competitively at the step (6).

$$\mathrm{Pd(O)\cdots O_2 + C_6H_6 \xrightarrow{k_1} C_6H_5\text{-}Pd(II)\text{-}OOH}$$

$$\mathrm{Pd(O)\cdots O_2 + C_6D_6 \xrightarrow{k_2} C_6D_5\text{-}Pd(II)\text{-}OOD}$$

Furthermore, two sets of the reactions may be considered at the step (7).

$$\mathrm{C_6H_5\text{–}Pd(II)\text{–}OOH + C_6H_6 \xrightarrow{k_3} C_6H_5\text{–}Pd\text{–}C_6H_5 + H_2O_2}$$

$$\mathrm{C_6H_5\text{–}Pd(II)\text{–}OOH + C_6D_6 \xrightarrow{k_4} C_6H_5\text{–}Pd\text{–}C_6D_5 + HDO_2}$$

$$\mathrm{C_6D_5\text{–}Pd(II)\text{–}OOD + C_6H_6 \xrightarrow{k_5} C_6D_5\text{–}Pd\text{–}C_6H_5 + HDO_2}$$

$$\mathrm{C_6D_5\text{–}Pd(II)\text{–}OOD + C_6D_6 \xrightarrow{k_6} C_6D_5\text{–}Pd\text{–}C_6D_5 + D_2O_2}$$

By the steady-state approximation for the concentration of C_6H_5–Pd(II)–OOH and C_6D_5–Pd(II)–OOD and using the same concentration of benzene and benzene-d_6, the reaction scheme mentioned above gives Eqs. (8 and 9) as follows;

$$d(\mathrm{C_6H_5\text{–}C_6H_5})/d(\mathrm{C_6D_5\text{–}C_6D_5}) = \frac{k_1k_3}{k_3+k_4} \times \frac{k_5+k_6}{k_2k_6} \quad (8)$$

$$d(\mathrm{C_6H_5\text{–}C_6D_5})/d(\mathrm{C_6D_5\text{–}C_6D_5}) = \frac{k_5+k_6}{k_2k_6} \times \left(\frac{k_1k_4}{k_3+k_4} + \frac{k_2k_5}{k_5+k_6}\right) \quad (9)$$

Considering the resemblance in the chemical properties between C_6H_5–Pd(II)–OOH and C_6D_5–Pd(II)–OOD, the ratio of k_3/k_4 is postulated to be close to k_5/k_6. Under the condition to make the difference of k_3/k_4 and k_5/k_6 to a minimum, k_3/k_4 is given to be 2.26.†† Accordingly, k_1/k_2 and k_5/k_6 are obtained as 2.49 and 2.10, respectively.

In the competitive reaction between benzene and benzene-d_6 in the presence of either toluene or *p*-xylene, the isotope effects on biphenyl are close to those in the simple system as seen in Table 1. In addition, the isotope effect of toluene–benzene/toluene–benzene-d_5 (2.19) may indicate the isomer ratio due to one step hydrogen abstraction from benzene, the order being comparable with one stage isotope effects calculated by us.

According to the mechanism postulated by Davidson and Triggs (*6*), isotope effect appears only in the stage of the formation of sigma-phenyl–palladium(II) complex which is followed by the intermolecular coupling to form biphenyl. On the contrary, the mechanism involving the two-step hydrogen abstraction from aromatic nucleus is able to account for not only isotope effects presented but also the isomer distributions of the coupling products (*14*).

To obtain more insight into the two-step hydrogen abstraction mechanism, the reaction was investigated using organomercury compounds such as *p*-tolyl- and phenylmercuric acetate. It is already known that these organomercury compounds are easily converted into aryl-palladium acetate intermediate (*2*, *15*) by the treatment of palladium(II) acetate at room temperature in the presence of perchloric acid.

p-Tolyl-palladium acetate intermediate was reacted at room temperature with benzene and benzene-d_6 to produce methyl biphenyl which consisted of 80.8% $CH_3C_6H_4$–C_6H_5 and 19.2% $CH_3C_6H_4$–C_6D_5 (k_H/k_D = 4.21). On the other hand, the mixture of benzene and benzene-d_6 was treated at room temperature concurrently with mercury(II) acetate and palladium(II) acetate in the presence of perchloric acid. There was formed biphenyl in which the ratios of biphenyl/biphenyl-d_{10} and biphenyl-d_5/biphenyl-d_{10} were 17.24 and 7.37, respectively.

Now, applying these values to Eqs. (8 and 9), we can obtain primary kinetic isotope effect of 5.07 for H-abstraction of palladium(II) acetate, and of 4.16 and 4.14 for H-abstraction of phenyl- and deuterophenyl-palladium acetate intermediate, respectively. These results are consistent with the mechanism proposed that palladium catalyzed coupling reaction of aromatic compounds proceeds through the two-step hydrogen abstraction, differing from the

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†† Using the mean values of C_6H_5–C_6H_5/C_6D_5–C_6D_5 and C_6H_5–C_6D_5/C_6D_5–C_6D_5 shown in Table 1, and then replacing k_1/k_2, k_3/k_4, k_5/k_6 with *a*, *b*, and *c*, respectively, the following relations are derived from Eqs. (8 and 9).

$$a = 5.11(b+1)/(5.34b - 5.11) \qquad c = 4.34 - (5.11/b)$$

So, using the relation $Y = (b - c)$, and subsequently evaluating the constant *b* to make *Y* a minimum, we can obtain *b* of 2.26.

mechanism suggested by Davidson and Triggs.

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