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Catalytic Hydration of Diethyl Maleate to Diethyl Malate Using Divalent Complexes of Palladium(II) as Catalysts

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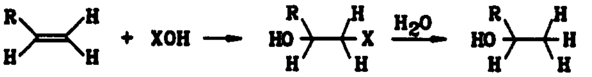
The complexes $[Pd(\mu\text{-}OH)(L\text{-}L)]_2^{2+}$ (L-L = dppe, dcpe) act as catalysts in aqueous THF solution for the addition of water to the carbon–carbon double bond of diethyl maleate to give the alcohol, diethyl malate. This addition reaction of diethyl maleate to give diethyl malate, as well as its oxidation to diethyl oxaloacetate, is catalyzed in aqueous THF solution by a mixture of $PdCl_4^{2-}$ and $CuCl_2$. Isomerization of diethyl maleate to diethyl fumarate, along with hydrolysis products of each alkene, is also observed with both catalyst systems. Mechanisms for these palladium(II) catalyzed reactions involving the protonolysis of an intermediate alkylpalladium complex are proposed. In aqueous solution, tertiary phosphines catalyze the *cis–trans* isomerization of diethyl maleate to diethyl fumarate.

Introduction

The addition of water to a carbon–carbon double bond is a potentially useful route for the synthesis of alcohols from alkenes (eq 1). From thermodynamic considerations

$$R_2C{=}CR_2 + H_2O \rightarrow R_2C(OH){-}CHR_2 \qquad (1)$$

for unactivated double bonds it is apparent that energetically such a hydration reaction is close to being thermoneutral.[1] The addition of water to a carbon–carbon double bond does not occur to any appreciable extent in the absence of a catalyst, and because of its thermoneutrality, it is likely that catalyzed systems will give reactions where the alkene, water, and the alcohol are in equilibrium with each other. The large scale production of ethyl alcohol by the hydration of ethylene involves the use of an acid catalyst. Among the acids used as catalysts for this reaction are sulfuric acid, phosphoric acid, and a proton-exchanged zeolite.[2] These catalyzed reactions, however, require both elevated temperatures and high acid concentrations and are therefore of rather limited value when sensitive functional groups are present on the alkene. The addition of water to an alkene can also be accomplished by the use of mercuric acetate.[3] These reactions with sulfuric acid and mercuric acetate involve an initial electrophilic attack at the alkene, followed by hydrolysis of the organosulfate or organomercurial intermediate to give the product alcohol (eq 2).



(2)

(X = OSO_3H, HgOAc)

Transition metal complexes have been used to effect the homogeneous hydration of *electron deficient* alkenes. For fluoro substituted alkenes, solutions containing chlororuthenate(II) species have been used as hydration catalysts,[4] and for fumaric and maleic acid, chromium(III) chloride has been used as the catalyst.[5] The mechanism of the chlororuthenate(II) catalyzed reaction is proposed to involve insertion of the carbon–carbon double bond of the alkene into the ruthenium–hydroxide bond. The hydration of electron deficient alkenes is also catalyzed enzymatically. Fumarase is such an enzyme that catalyzes the equilibration reaction between fumarate and malate ions.[6] The enzyme does not, however, involve a metal ion at the active site, and primary and secondary isotope effect studies have demonstrated that the transition state involves reaction at a carbanionic center.[7]

In this paper we report our results on the use of hydroxy-bridged dipalladium(II) complexes of type $[Pd(\mu\text{-}OH)(L\text{-}L)]_2^{2+}$ as catalysts for the hydration of diethyl maleate to diethyl malate.[8] In addition, we now report that a catalyst consisting of a mixture of $PdCl_4^{2-}$ and $CuCl_2$ in an aqueous THF solution can also be used to catalyze this hydration reaction. The catalyzed reaction between alkenes and water with a mixture of $PdCl_4^{2-}$ and $CuCl_2$ usually leads to the formation of an aldehyde or a ketone,[9] and we believe that this is the first time that the use of such a catalyst has resulted in the formation of an alcohol by the addition of water to the carbon–carbon bond of an alkene. The difference between the two systems is that $[Pd(\mu\text{-}OH)(L\text{-}L)]_2^{2+}$ is catalytic in the absence of added cupric ion, but that $PdCl_4^{2-}$ requires the presence of cupric ion to achieve a turnover number of greater than unity.

Experimental Section

General Procedure. Diethyl maleate, diethyl fumarate, ethyl crotonate, methyl acrylate, sodium styrene-4-

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sulfonate, and 1-octene were commercial samples and used as supplied. 1,2-Bis(diphenylphosphino)ethane (dppe), triphenylphosphine, methyldiphenylphosphine, diphenylphosphine, tricyclohexylphosphine, sodium 2-bromoethanesulfonate, diethyl (2-bromoethyl)phosphonate, bromotrimethylsilane and D_2O were obtained from Aldrich Chemical Co. 1,2-Bis(dicyclohexylphosphino)ethane (dcpe) was obtained from Strem Chemicals, and copper(II) chloride, sodium tetrafluoroborate, sodium chloropalladate, *n*-butyllithium, sodium, and ammonia were also commercial samples. The complexes $Pd(dppe)Cl_2$, $[Pd(\mu\text{-}OH)(PMePh_2)_2]_2(BF_4)_2$, $[Pd(\mu\text{-}OH)(dppe)]_2(BF_4)_2$, $[Pd(\mu\text{-}OH)(PPh_3)_2]_2(BF_4)_2$, and $[Pd(\mu\text{-}OH)(dcpe)]_2(BF_4)_2$ were synthesized using literature procedures.[10] Diethyl malate was supplied by Pfaltz & Bauer Inc. The compound $(EtO_2C)CH(OD)CH_2(CO_2Et)$ was prepared by stirring $(EtO_2C)CH(OH)CH_2(CO_2Et)$ (0.5 g, 0.26 mmol) in D_2O (1 g, 50 mmol of 99.96 atom % D) at 23 °C for 24 h under an atmosphere of argon. The product was purified by extraction with dichloromethane, followed by evaporation of this solvent.

The water soluble ligands were synthesized under an argon atmosphere. All solvents were purged with dry nitrogen prior to use. Nuclear magnetic resonance spectra were recorded on either a Bruker AC 200 or GE Omega 400 or 500 spectrometers as solutions in deuterated solvents. Fast atom bombardment (FAB) mass spectra were obtained using a Kratos Concept 1H mass spectrometer with the samples introduced in a *m*-nitrobenzyl alcohol matrix. Infrared spectra were recorded on a Mattson Cygnus 100 FT-IR spectrometer with the samples compressed in potassium bromide pellets.

Catalytic Reactions. The catalytic reactions were carried out in thick-walled glass tubes. The tubes containing the reaction mixture and a magnetic stir bar were sealed under argon. The glass tubes were heated in an oil bath, and the mixture was stirred on a magnetic stirrer. After the reaction was complete, the tube was allowed to cool and the reaction mixture was filtered through alumina. The organic products in the filtrate were then analyzed on a Hewlett-Packard Model 5830 GC–mass spectrometer. Deuterium labeling studies were carried out using 99.96% D_2O (Aldrich Chemicals) in place of water. Fragmentation intensity comparisons with authentic samples were carried out using a Kratos Concept 1H GC–mass spectrometer. Product alcohol yields were obtained by integration of the baseline resolved peaks in the printed GC–mass spectra after correcting for the relative sensitivities of the compounds. The yield of diethyl oxaloacetate was obtained from the integrated area of its parent ion peak against the parent ion peak of diethyl malate.

Formation and Analysis of $(EtO_2C)CH(OD)CHD(CO_2Et)$. The compound $(EtO_2C)CH(OD)CHD(CO_2Et)$ was prepared by heating a mixture of diethyl maleate (3.1 mmol) and D_2O (56 mmol) with $[Pd(\mu\text{-}OH)(dppe)]_2(BF_4)_2$ (16.1 μmol) in THF (3 mL), or of diethyl maleate (3.1 mmol) and D_2O (56 mmol) with Na_2PdCl_4 (16.1 μmol) and $CuCl_2$ (33 μmol), for 30 h at 130 °C. The reaction mixture in each case was filtered through alumina, and the organic products were analyzed by GC–mass spectrometry. The quantities of the diastereomeric *threo* and *erythro* forms were determined by integration of the baseline-separated peaks.

Sodium 2-(Diphenylphosphino)ethanesulfonate, $Ph_2PCH_2CH_2SO_3Na$. Synthesis Using Ammonia as Solvent. Ammonia (200 mL) was condensed through a barium oxide drying tube into a 500-mL three-necked round-bottom flask, fitted with a dry ice condenser, a mechanical stirrer, and an argon inlet tube. Freshly cut sodium (1.45 g, 63 mmol) in *ca.* 100-mg pieces was slowly added to it with stirring. The blue colored solution was stirred for 1 h over a dry ice–acetone bath under argon at −78 °C. Triphenylphosphine (8.25 g, 31.5 mmol) was then added in small amounts over a period of 1 h. The red solution was vigorously stirred for 1.5 h. Dry ammonium chloride (1.68 g, 31.4 mmol) was then slowly added under argon, which converted the phenylsodium into sodium chloride and benzene. After this red-orange solution was stirred for 1 h, sodium 2-bromoethanesulfonate (6.65 g, 31.5 mmol) was added in small portions over 0.5 h with vigorous stirring. Dry THF (150 mL) was syringed into the reaction, and the mixture was stirred overnight to allow for the evaporation of ammonia. The THF was removed under vacuum, and a deoxygenated mixture of dichloromethane (50 mL) and water (100 mL) was added to the cream colored residue. The dichloromethane layer was discarded to leave the aqueous layer. The water soluble product was isolated by evaporation of the solvent, followed by drying under vacuum to yield a white solid. This solid was then dissolved in the minimum amount of hot dry methanol. Upon slow cooling of the solution, the white crystalline product precipitated. The compound was filtered out and dried in vacuum. Yield: 7.85 g (79.4%). ^1H NMR (D_2O): δ 2.41–2.46 (m, 2H, PCH_2), 2.76–2.85 (m, 2H, SCH_2), 7.33–7.48 (m, 10H, phenyl). $^{31}P\{^1H\}$ NMR (D_2O): δ −16.5 (s). $^{13}C\{^1H\}$ NMR (D_2O): δ 22.3 (d, CH_2, $^2J(PC)$ = 11 Hz), 48.2 (d, CH_2, $^1J(PC)$ = 18 Hz), 129.4 (d, (phenyl, $J(PC)$ = 6 Hz), 131.3 (s, phenyl), δ 133.1 (d, phenyl, $J(PC)$ = 19 Hz), 137.0 (d, phenyl, $J(PC)$ = 9 Hz). IR (KBr pellet): $\nu(CH_2)$ 2922, $\nu(CH_2)$ 2850, $\nu(SO)$ 1435, $\nu(SC)$ 1251, $\nu(SO)$ 1172, $\nu(S{=}O)$ 1068, $\delta(CH)$ 725, $\delta(CH)$ 705 cm^{-1}. Microanalytical data were not obtained for the compound because of its being highly hygroscopic.

Synthesis Using Tetrahydrofuran as Solvent. Alternatively, in a predried 100-mL round bottom flask purged thoroughly with argon, diphenylphosphine (4.0 mL, 23 mmol) was syringed in followed by dry THF (25 mL). After the solution was cooled to 0 °C, 2.5 M *n*-butyllithium (9.4 mL, 23.4 mmol) was added dropwise while the solution was stirred. The reaction mixture was then stirred vigorously for 2 h, and to this intense red solution was added dropwise with stirring over a period of 0.5 h sodium 2-bromoethanesulfonate (4.85 g, 23 mmol) in dry THF (25 mL) suspension. The reaction mixture was then allowed to slowly warm to room temperature over a period of approximately 3 h. The solvents were then removed under vacuum, and the white crystalline product was obtained as before in approximately 80% yield.

Disodium [2-(Diphenylphosphino)ethyl]phosphonate, $Ph_2PCH_2CH_2P(O)O_2Na_2$. A predried 100-mL round-bottom flask was purged thoroughly with argon, and diphenylphosphine (4.0 mL, 23 mmol) was added to it followed by dry THF (25 mL). After the solution was cooled to 0 °C, 2.5 M *n*-butyllithium in hexane (9.4 mL, 23.4 mmol) was added dropwise, and the solution was stirred for 2 h. The solution was then further cooled to −78 °C in a dry ice–acetone bath. To this intense red solution at −78 °C was added dropwise diethyl (2-

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[10] Ganguly, S.; Mague, J. T.; Roundhill, D. M. *Inorg. Chem.* **1992**, *31*, 3831.

bromoethyl)phosphonate (4.5 mL, 23 mmol) in dry THF (20 mL), and the solution was stirred for 2 h. After evaporation of the solvent on a rotary evaporator, a viscous colorless liquid remained. This viscous liquid was extracted into dichloromethane (50 mL), the solution was filtered, and the solvent was then removed under vacuum to give the compound diethyl [2-(diphenylphosphino)ethyl]phosphonate, $Ph_2PCH_2CH_2P(O)(OEt)_2$, as a clear colorless liquid. Yield: 7.5 mL (95%). ^1H NMR ($CDCl_3$): δ 1.26 (m, 6H, CH_3, J = 8 Hz), 1.7–2.0 (m, 2H, P_ACH_2), 2.25–2.55 (m, 2H, P_BCH_2), 4.0–4.1 (m, 4H, OCH_2), 7.3–7.75 (m, 10H, phenyl). $^{31}P\{^1H\}$ NMR ($CDCl_3$): δ −12.3 (d, P_A), −31.9 (d, P_B, $^3J(PP)$ = 63 Hz). $^{13}C\{^1H\}$ NMR ($(CD_3)_2CO$): δ 16.6 (d, CH_3, $^3J(P_BC)$ = 6 Hz), 22.5 (dd, CH_2P_B, $^1J(P_BC)$ = 140 Hz, $^2J(P_AC)$ = 22 Hz), 23.1 (dd, P_ACH_2, $^1J(P_AC)$ = 62 Hz, $^2J(P_BC)$ = 3 Hz), 62.0 (dd, OCH_2, $^2J(P_BC)$ = 25 Hz, $^5J(P_AC)$ = 6 Hz), 129.3 (s), 129.4 (d, $J(PC)$ = 2 Hz), 129.5 (d, $J(PC)$ = 2 Hz), 129.6 (s), 131.4 (d, $J(PC)$ = 10 Hz), 133.3 (d, $J(PC)$ = 19 Hz). The $^{13}C\{^1H\}$ NMR peaks in the range δ 129.3–133.3 are due to phenyl carbons. IR (KBr pellet): $\nu(CH_3)$ 2932, $\nu(CH_2)$ 2864, $\delta(CH_2)$ 1452, $\nu(P{=}O)$ 1296, $\nu(P{=}O)$ 1246, $\nu(PPh)$ 1124, $\nu(PPh)$ 1097, $\nu(PO)$ 1058, $\nu(PO)$ 1031, $\nu(PO)$ 960, $\delta(CH)$ 736, $\delta(CH)$ 696 cm^{-1}. Mass spectrum: m/e 350.1192. Calc for $C_{18}H_{24}O_3P_2$: m/e 350.1120. The compound is oxidized in the presence of air to give the phosphine oxide $Ph_2P(O)CH_2CH_2P(O)(OEt)_2$. $^{31}P\{^1H\}$ NMR ($CDCl_3$): δ 31.3 (d, P_B), δ 33.3 (d, P_A, $^3J(PP)$ = 68 Hz).[11]

An aliquot (2 mL) of the freshly prepared diethyl [2-(diphenylphosphino)ethyl]phosphonate was taken in a predried 50-mL round bottom flask, and dichloromethane (15 mL) was added. The solution was rapidly stirred, and trimethylbromosilane (10 mL) was added under an atmosphere of argon. After the mixture was stirred for 13 h, the excess trimethylbromosilane and the dichloromethane solvent were removed under vacuum, to give the pure compound bis(trimethylsilyl) [2-(diphenylphosphino)ethyl]phosphonate, $Ph_2PCH_2CH_2P(O)(OSiMe_3)_2$, as a colorless solid. ^1H NMR ($CDCl_3$): δ 0.3 (s, 18H, CH_3), 2.1 (m, 2H, CH_2P_A), δ 3.1 (m, 2H, CH_2P_B), 7.5–8.0 (m, 10H, phenyl). $^{31}P\{^1H\}$ NMR (D_2O): δ −5.8 (m, P_A), 11.5 (d, P_B, $^3J(PP)$ = 62 Hz).

The bis(trimethylsilyl) [2-(diphenylphosphino)ethyl]phosphonate obtained in the previous step was dissolved in dichloromethane (10 mL), and then deoxygenated water (10 mL) was added while the mixture was stirred. This procedure gave the compound $Ph_2PCH_2CH_2P(O)(OH)_2$ in the aqueous layer. $^{31}P\{^1H\}$ NMR ($CDCl_3$): δ −12.2 (d, P_A), 25.0 (d, P_B, $^3J(PP)$ = 63 Hz). This compound was then converted into its disodium salt in aqueous solution by the addition of 6 N NaOH (1 mL). Evaporation of the solvent gave the compound disodium [2-(diphenylphosphino)ethyl]phosphonate as a colorless solid, $Ph_2PCH_2CH_2P(O)O_2Na_2$, in quantitative yield. ^1H NMR (D_2O): δ 1.26–1.52 (m, 2H, CH_2P_A), 2.22–2.28 (m, 2H, CH_2P_B), 7.35–7.68 (m, 10H, phenyl). $^{31}P\{^1H\}$ NMR (D_2O): δ −11.3 (d, P_A), 22.3 (d, P_B, $^3J(PP)$ = 63 Hz). $^{13}C\{^1H\}$ NMR (D_2O): δ 24.4 (dd, CH_2P_A, $^1J(P_AC)$ = 70 Hz, $^2J(P_BC)$ = 4 Hz), 25.9 (dd, CH_2P_B, $^1J(P_BC)$ = 128 Hz, $^2J(P_AC)$ = 12 Hz), 129.6 (d, $J(PC)$ = 30 Hz), 131.3 (d, $J(PC)$ = 10 Hz), 133.3 (d, $J(PC)$ = 18 Hz), 138.1 (d, $J(PC)$ = 7 Hz). IR (KBr pellet): $\nu(CH_2)$ 2868, $\nu(CH_2)$ 2845, $\delta(CH_2)$ 1461, $\nu(P{=}O)$ 1305, $\nu(P{=}O)$ 1159, $\nu(PPh)$ 1122, $\nu(P{-}O)$ 1072, $\nu(P{-}O)$ 976 cm^{-1}. Microanalytical data were not obtained for the compound because of its being highly hygroscopic.

Results

Catalytic Hydration of Diethyl Maleate with $[Pd(\mu\text{-}OH)(L\text{-}L)]_2^{2+}$ and with a Mixture of $PdCl_4^{2-}$ and $CuCl_2$. The homogeneous hydration of the carbon–carbon double bond in diethyl maleate, *cis*-$(EtO_2C)CH{=}CH(CO_2Et)$ to give the alcohol, diethyl malate, $(EtO_2C)CH(OH)CH_2(CO_2Et)$ requires a palladium(II) complex as catalyst. The catalyzed reaction can be carried out at temperatures between 120 and 140 °C in aqueous THF as solvent. Attempts to achieve the direct hydration of diethyl maleate under the same experimental conditions in the absence of any catalyst does not yield any detectable amounts of diethyl malate. We find that the hydration of diethyl maleate can be catalyzed by (μ-hydroxy)palladium(II) complexes and by a catalyst mixture containing $PdCl_4^{2-}$ and $CuCl_2$. Thus when a mixture containing the (μ-hydroxy)palladium(II) complex $[Pd(\mu\text{-}OH)(L\text{-}L)]_2^{2+}$ (L-L = 1,2-bis(diphenylphosphino)ethane (dppe) or 1,2-bis(dicyclohexylphosphino)ethane (dcpe)), diethyl maleate, water, and THF, in a respective mol ratio of 1:190:3415:2540 is allowed to react at a temperature of 120 °C for 30 h, the alcohol diethyl malate is formed (eq 3). The

$$(EtO_2C)CH{=}CH(CO_2Et) + H_2O \xrightarrow{[Pd(\mu\text{-}OH)(L\text{-}L)]_2^{2+}} (EtO_2C)CH(OH)CH_2(CO_2Et) \quad (3)$$

L-L = dppe, dcpe

conversion to diethyl malate is 2.6 and 2.9 mol/mol of the palladium(II) complex $[Pd(\mu\text{-}OH)(L\text{-}L)]_2^{2+}$, for L-L being dppe and dcpe, respectively. This conversion yield of alcohol at 120 °C is small, but it does represent a catalyzed reaction based on the palladium(II) complex. At lower reaction temperatures (≤100 °C), no conversion to diethyl malate is observed. For the complex $[Pd(\mu\text{-}OH)(dppe)]_2^{2+}$, the other products formed in the reaction are diethyl fumarate (*trans*-$(EtO_2C)CH{=}CH(CO_2Et)$) (14 mol), fumaric acid monoethyl ester (*trans*-$(EtO_2C)CH{=}CH(CO_2H)$) (15 mol), and maleic acid (*cis*-$(HO_2C)CH{=}CH(CO_2H)$) or its anhydride ($(CH{=}CH)(O_2CO)$) (12 mol). We observe no formation of the alkene oxidation product diethyl oxaloacetate ($(EtO_2C)CH_2C(O)CO_2Et$)). After the 30-h reaction time, the complexes $[Pd(\mu\text{-}OH)(L\text{-}L)]_2^{2+}$ have decomposed to palladium metal, along with the tertiary phosphine oxide as the oxidation product. The palladium metal that is formed is catalytically inactive for the hydration reaction. The catalyzed hydration reaction is irreversible, since no detectable quantities of diethyl maleate are formed from diethyl malate in the presence of $[Pd(\mu\text{-}OH)(L\text{-}L)]_2^{2+}$ under the same reaction conditions that lead to the formation of diethyl malate.

An approximate 5-fold increase, from a mol ratio of 2.6 to 13.9 based on the catalyst concentration, is observed in the conversion of diethyl maleate into diethyl malate when the reaction is carried out at the higher temperature of 140 °C rather than 120 °C in the presence of catalytic quantities of $[Pd(\mu\text{-}OH)dppe]_2^{2+}$. Temperatures above 140 °C do not, however, give higher conversions to diethyl malate. The complexes $[Pd(\mu\text{-}OH)(PPh_3)_2]_2^{2+}$ and $[Pd(\mu\text{-}OH)(PMePh_2)_2]_2^{2+}$ that have monodentate rather than

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[11] The structure of this compound has been verified by an X-ray crystal structure determination of a palladium complex prepared from it. See: Ganguly, S.; Mague, J. T.; Roundhill, D. M. *Inorg. Chem.* **1992**, *31*, 3500.

Table I. Conversion of Diethyl Maleate into Diethyl Fumarate, Maleic Acid and Its Anhydride, Fumaric Acid Monoethyl Ester and Diethyl Malate[a]

	mol ratio of products			
catalyst	diethyl fumarate	maleic acid	fumaric acid monoethyl ester	diethyl malate
$[Pd(\mu\text{-}OH)(dppe)]_2^{2+}$ [b]	9.5	<1.0	<1.0	<1.0
$[Pd(\mu\text{-}OH)(dppe)]_2^{2+}$ [c]	14.3	12.4	14.5	2.6
$[Pd(\mu\text{-}OH)(dppe)]_2^{2+}$	17.3	24.0	28.1	14.1
$[Pd(\mu\text{-}OH)(dcpe)]_2^{2+}$ [c]	15.6	13.4	12.9	2.9
$[Pd(\mu\text{-}OH)(dcpe)]_2^{2+}$	16.8	22.4	27.1	14.3
$[Pd(\mu\text{-}OH)(dppe)]_2^{2+}$ [d]	19.3	28.4	27.0	13.9
$[Pd(\mu\text{-}OH)(PPh_3)_2]_2^{2+}$	12.6	8.9	14.6	<1.0
$[Pd(\mu\text{-}OH)(PMePh_2)_2]_2^{2+}$	13.4	14.6	11.2	<1.0
$[Pd(\mu\text{-}OH(dppe))]_2^{2+}$ (pH 8)[e]	7.5	3.6	19.1	<1.0
$[Pd(\mu\text{-}OH)(dppe)]_2^{2+}$ (pH 10)[e]	20.2	<1.0	19.2	<1.0
$[Pd(\mu\text{-}OH)(dppe)]_2^{2+}$ (pH 12)[e]	17.8	<1.0	<1.0	<1.0
$[Pd(\mu\text{-}OH)(dppe)]_2^{2+}$ (pH 2)[f]	<1.0	170.0	4.6	<1.0
$[Pd(\mu\text{-}OH)(dppe)]_2^{2+}$ (pH 3)[f]	<1.0	175.0	3.3	<1.0
$[Pd(\mu\text{-}OH)(dppe)]_2^{2+}$ (pH 4)[f]	<1.0	178.3	4.5	<1.0
$[Pd(\mu\text{-}OH)(dppe)]_2^{2+}$ (pH 5)[f]	<1.0	174.7	3.8	<1.0
$[Pd(\mu\text{-}OH)(dppe)]_2^{2+}$ + $CuCl_2$[g]	5.7	133.3	2.5	2.0
$[Pd(\mu\text{-}OH)(dppe)]_2^{2+}$ + Hg[h]	38.0	76.0	43.7	13.8
$PdCl_2(dppe)$[i]	60.4	<1.0	1.4	<1.0
$PdCl_2(dppe)$ + $NaBF_4$ (pH 9)[j]	13.3	89.5	67.5	<1.0
$PdCl_2(dppe)$ + $NaBF_4$ (pH 10)[j]	20.9	17.7	112.1	1.0
$PdCl_2(dppe)$ + $NaBF_4$ (pH 11)[j]	14.5	4.4	73.4	1.8

[a] These reactions were carried out with stirring in a sealed glass tube containing the metal complex (16.4 μmol), diethyl maleate (3.1 mmol), H_2O (56 mmol), THF (42 mmol) at 140 °C for 30 h. The molar ratio of product formation (turnover) is based on the number of moles of product formed per mole of the catalyst used. [b] Reaction conditions: 30 h at 100 °C. [c] Reaction conditions: 30 h at 120 °C. [d] Reaction conditions: 60 h at 140 °C. [e] Solution prepared at this pH by the addition of 1 M NaOH. [f] Solution prepared at this pH by the addition of 1 M H_3PO_4. [g] Quantity of $CuCl_2$ added is 1.5×10^{-4} mol. [h] Quantity of Hg added is 2.0×10^{-4} mol. [i] Quantity of complex is 3.0×10^{-5} mol. [j] These reactions were carried out in a sealed glass tube with $Pd(dppe)Cl_2$ (35 μmol), $NaBF_4$ (0.18 mmol), H_2O (56 mmol), THF (42 mmol), 1 M NaOH, an diethyl maleate (3.1 mmol) at 140 °C for 30 h.

bidentate tertiary phosphine ligands show no catalytic activity for the hydration of diethyl maleate at 140 °C. The quantities of the different products obtained for the reaction of diethyl maleate with water in the presence of the complexes $[Pd(\mu\text{-}OH)L_2]_2^{2+}$ and $[Pd(\mu\text{-}OH)(L\text{-}L)]_2^{2+}$ are collected in Table I. These data show that the products are diethyl fumarate, formed by the catalyzed isomerization of diethyl maleate, maleic acid, and fumaric acid monoethyl ester, formed by the hydrolysis of diethyl maleate and diethyl fumarate, respectively, and the alcohol, diethyl malate. Since the hydrolysis of the ester groups in diethyl maleate during the catalyzed reaction leads to the formation of malic acid and fumaric acid monoethyl ester, a reaction has been carried out with diethyl maleate and $[Pd(\mu\text{-}OH)(L\text{-}L)]_2^{2+}$ in a water–ethanol mixture (1:1 by volume) in order to determine whether such solvent conditions will inhibit this hydrolysis reaction. No decrease in the conversion to the hydrolyzed products is observed. Only diethyl maleate undergoes the catalyzed hydration reaction. Thus when the hydration reactions of diethyl fumarate, maleic acid, or the anhydride are separately attempted in the presence of $[Pd(\mu\text{-}OH)(L\text{-}L)]_2^{2+}$, no conversion to malic alcohols is observed. Experiments have also been carried out to determine whether controlling the pH of the reaction mixture affects the quantitative conversion of diethyl maleate into diethyl malate. The pH of the reaction mixture has been varied by adding sodium hydroxide or phosphoric acid to obtain solutions having different pH values of 2, 3, 4, 5, 8, 10, and 12. We find that in either acid or base solution that the conversion of diethyl maleate into diethyl malate in the catalyzed reaction is reduced.

In order to verify that the palladium complex $[Pd(\mu\text{-}OH)(dppe)]_2(BF_4)_2$ is indeed the active catalyst and that the reaction is not being catalyzed by one of the other components in the solution, we have verified that a mixture of diethyl maleate in the presence of water, $NaBF_4$, and free dppe at 140 °C does not yield any detectable diethyl malate. The only detectable product in this reaction mixture is the *trans* isomer of the alkene, diethyl fumarate (180 mol/mol of added dppe).

Since at the end of the catalyzed reaction the complexes $[Pd(\mu\text{-}OH)(L\text{-}L)]_2^{2+}$ have been converted to palladium metal and the oxidized tertiary phosphine, it is necessary to determine whether palladium itself is acting as a heterogeneous catalyst for the reaction. A technique for probing whether a reaction in solution is being catalyzed homogeneously, or whether it is actually being catalyzed heterogeneously by finely dispersed metal, is to add elemental mercury to the mixture. A decrease in the conversion to products upon addition of mercury is suggestive of a heterogeneously catalyzed reaction.[12] In the presence of added mercury, the yield of diethyl malate from diethyl maleate in the presence of $[Pd(\mu\text{-}OH)dppe]_2^{2+}$ remains unchanged. Also, no increase in the conversion to diethyl malate is observed if the reaction time is extended from 30 to 60 h. If the palladium metal deposited after the decomposition of the complex was the actual catalyst, it is likely that the catalytic hydration reaction would continue beyond the 30-h reaction time when all of the $[Pd(\mu\text{-}OH)(L\text{-}L)]_2^{2+}$ has been converted into palladium metal. When $Pd(dppe)Cl_2$ (1 mol), which is the precursor complex to $[Pd(\mu\text{-}OH)dppe]_2^{2+}$, is added to a mixture of diethyl maleate, THF, water, $NaBF_4$, and 1 M NaOH at 140 °C, small amounts of diethyl malate are detected.

Catalytic Hydration of Diethyl Maleate with D_2O. When the catalyzed hydration of diethyl maleate is carried out at 140 °C for 30 h with D_2O present in place of H_2O, deuterated diethyl malate is formed. To confirm that we

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(12) (a) Anton, D. R.; Crabtree, R. H. *Organometallics* **1983**, *2*, 855. (b) Collman, J. P.; Kosydar, K. M.; Bressan, M.; Lamanna, W.; Garrett, T. *J. Am. Chem. Soc.* **1984**, *106*, 2569. (c) Whitesides, G. M.; Hackett, M.; Brainard, R. L.; Lavalleye, J.-P. P. M.; Sowinski, A. F.; Izumi, A. N.; Moore, S. S.; Brown, D. W.; Staudt, E. M. *Organometallics* **1985**, *4*, 1819.

Table II. Mass Spectral Comparison of the Relative Intensities of the Highest Mass Groups of Diethyl Malate[a]

	($RCH_2CH(OH)R$)		
mass	A intensity	B intensity	C intensity
144	281	226	399
145	759	623	1109
190	17	12	23
191	95	28	112

	($RCH_2CH(OD)R$)		($RCHDCH(OD)R$)
mass	D intensity	mass	E intensity
145	5383	146	4849
146	3955	147	1530
191	340	192	490
192	300	193	229

[a] Sample A: authentic commercial sample of $RCH_2CH(OH)R$ ($R = CO_2Et$). Sample B: alcohol formed in a reaction carried out at 140 °C for 30 h which contains diethyl maleate, water, THF, and $[Pd(\mu\text{-}OH)(dppe)]_2^{2+}$ (see Table I). Sample C: alcohol formed in a reaction carried out at 140 °C for 30 h which contains diethyl maleate, water, THF, and a mixture of Na_2PdCl_4 and $CuCl_2$ (see Table III). Sample D: authentic commercial sample of $RCH_2CH(OH)R$ ($R = CO_2Et$) stirred in 99.96% D_2O at 23 °C for 24 h. Sample E: alcohol formed in a reaction carried out at 140 °C for 30 h which contains diethyl maleate, 99.96% D_2O, THF, and $[Pd(\mu\text{-}OH)(dppe)]_2^{2+}$ (see Table I).

are indeed forming diethyl malate in the catalyzed reaction, the relative abundances of both the protonated and the deuterated products that are formed have been compared with authentic samples of $(EtO_2C)CH(OH)CH_2(CO_2Et)$ and $(EtO_2C)CH(OD)CH_2(CO_2Et)$. These products have been characterized by the use of high resolution GC–mass spectroscopy. The mass spectroscopic data (samples A through E) are collected in Table II. For pure $(EtO_2C)CH(OH)CH_2(CO_2Et)$ (sample A) we observe the highest masses at m/e 190 and 191, which correspond to the m and $m + 1$ peaks, respectively. A second pair of diagnostic peaks are observed at m/e 145 and 146, and these are peaks that correspond to the loss of a molecule of EtOH from m and $m + 1$. Samples B and C are the organic products obtained in the catalyzed reactions with $[Pd(\mu\text{-}OH)(dppe)]_2^{2+}$ and the mixture of $PdCl_4^{2-}$ and Cu^{2+}, respectively. The close correspondence between the mass ratios of the peaks from samples B and C and the authentic sample A of diethyl malate confirms that diethyl malate is being formed in the catalyzed reactions. Sample D is a synthetic sample of monodeuteriomalic acid $(EtO_2C)CH(OD)CH_2(CO_2Et)$, prepared by the exchange reaction between $(EtO_2C)CH(OH)CH_2(CO_2Et)$ and D_2O. Sample E is the organic product $(EtO_2C)CH(OD)CHD(CO_2Et)$ formed in the catalyzed reaction with $[Pd(\mu\text{-}OH)(dppe)]_2^{2+}$ in D_2O (eq 4). This systematic increase in the highest

$$cis\text{-}(EtO_2C)CH{=}CH(CO_2Et) + D_2O \rightarrow (EtO_2C)CH(OD)CHD(CO_2Et) \quad (4)$$

mass peaks of the nondeuterated and the mono- and dideuterated diethyl malates by a single amu provides good evidence for the formation of dideuterated diethyl malate in the catalyzed addition of D_2O to diethyl maleate.

The catalyzed addition of D_2O to cis-$(EtO_2C)CH{=}CH(CO_2Et)$ in the presence of both $[Pd(\mu\text{-}OH)(dppe)]_2^{2+}$ and a mixture of $PdCl_4^{2-}$ and Cu^{2+} as catalyst gives the *threo* and *erythro* isomers of $(EtO_2C)CH(OD)CHD(CO_2Et)$ in approximately equal amounts.[13] This result correlates with the observed formation of the isomerized products diethyl fumarate and monoethyl fumarate in the catalyzed addition of H_2O to diethyl maleate using $[Pd(\mu\text{-}OH)(dppe)]_2^{2+}$ as catalyst, and in the formation of diethyl fumarate and fumaric acid monoethyl ester using a mixture of $PdCl_4^{2-}$ and Cu^{2+} as catalyst. The stereoselectivity is likely being lost by free rotation in an alkylpalladium(II) intermediate complex, which is an analogous pathway to that which causes the isomerization of diethyl maleate to the *trans* isomer.

Since the complex $[Pd(\mu\text{-}OH)(dppe)]_2^{2+}$ is reduced to palladium metal during the catalyzed reaction, copper(II) chloride has been added to the reaction mixture in order to reoxidize it back to Pd(II), and possibly extend the life of the catalyst. The addition of copper(II) chloride, however, reduces the conversion of diethyl malate from 14 to 2 mol/mol of catalyst used rather than increasing it. Although the presence of copper(II) chloride results in a decrease in the conversion of diethyl maleate into diethyl malate in the $[Pd(\mu\text{-}OH)(dppe)]_2^{2+}$ catalyzed reaction, aqueous THF solutions containing sodium chloropalladate and copper(II) chloride in the absence of $[Pd(\mu\text{-}OH)(L\text{-}L)]_2^{2+}$ do, however, catalyze the hydration of diethyl maleate to diethyl malate. Thus we find that a catalyst mixture containing 1 mol of sodium chloropalladate yields 15 mol of diethyl malate from a mixture of diethyl maleate in THF and water at 140 °C. The turnover number for the conversion of diethyl maleate into diethyl malate in the presence of a catalyst composed of a mixture of $PdCl_4^{2-}$ and Cu^{2+} is therefore close to that obtained with the complexes $[Pd(\mu\text{-}OH)(dppe)]_2^{2+}$. A significant difference between the mixture of $PdCl_4^{2-}$ and Cu^{2+} and $[Pd(\mu\text{-}OH)(dppe)]_2^{2+}$ as catalysts, however, is that in the former system considerable quantities of the oxidation product, diethyl oxaloacetate, are formed whereas no such oxidation product is detected using $[Pd(\mu\text{-}OH)(dppe)]_2^{2+}$ as catalyst.

As a further means to try and reduce the amount of decomposition of the complex $[Pd(\mu\text{-}OH)(dppe)]_2^{2+}$ during the catalytic reaction, we have also added free dppe to the solution. The addition of 1 equiv of dppe to the solution causes no increase in the yield of the alcohol, but the subsequent addition of 2, 3, 4, and 6 equiv of dppe decreases the yield from 14 mol of diethyl malate/mol of $[Pd(\mu\text{-}OH)(dppe)]_2^{2+}$ to less than 2 mol. This decrease in the conversion into diethyl malate with added dppe correlates with a corresponding increase in the yield of diethyl fumarate from 15 to 170 mol (Table III). For the Wacker catalyzed reaction with $PdCl_4^{2-}$ and $CuCl_2$, the addition of 5 mol equiv of the tertiary phosphines $Ph_2PCH_2CH_2SO_3Na$, $Ph_2PCH_2CH_2P(O)(ONa)_2$, PPh_3, of dppe, per mol of sodium chloropalladate to the solution of diethyl maleate leads to the formation of diethyl fumarate (4–26 mol/mol of $PdCl_4^{2-}$ added), but no formation of diethyl malate. No decrease in the formation of palladium metal is observed under these experimental conditions. This experiment was carried out to determine whether we could prepare a two-stage catalyst where the palladium obtained in the formation of diethyl malate in the reductive cycle can be stabilized as a zerovalent complex by the tertiary phosphine, so that this complex can act as a homogeneous catalyst for the formation of diethyl malate in an oxidative cycle where the first step is the addition of water to the Pd(0) complex.

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(13) For other systems the identification of a single diastereomer has been used to determine the stereochemistry of the attack by water at a coordinated alkene. See: (a) Bäckvall, J. E.; Akermark, B.; Ljunggren, S. O. *J. Am. Chem. Soc.* **1979**, *101*, 2411. (b) Zaw, K.; Henry, P. M. *Organometallics* **1992**, *11*, 2008.

Table III. Effects of Tertiary Phosphines in the Presence of $[Pd(\mu\text{-}OH)(dppe)]_2^{2+}$ and Na_2PdCl_4 in the Reaction between Diethyl Maleate and Water[a]

	mol ratio of products			
catalyst	diethyl fumarate	malic acid	fumaric acid monoethyl ester	diethyl malate
$PdCl_4^{2-}$	2.3	12.0	11.3	1.2
$PdCl_4^{2-}$ [b]	4.3	16.5	24.1	15.3
$PdCl_4^{2-} + Ph_2PCH_2CH_2P(O)O_2^{2-}$ [b,c]	8.4	13.2	19.9	2.2
$PdCl_4^{2-} + Ph_2PCH_2CH_2SO_3^{-}$ [b,c]	3.4	16.8	14.3	<1.0
$PdCl_4^{2-}$ + dppe[b,c]	26.3	20.6	17.5	<1.0
$Na_2PdCl_4 + PPh_3$[b,c]	22.3	14.8	20.6	<1.0
$[Pd(\mu\text{-}OH)(dppe)]_2^{2+}$ + dppe (16.4 μmol)	18.4	23.8	27.5	13.8
$[Pd(\mu\text{-}OH)(dppe)]_2^{2+}$ + dppe (32.8 μmol)	54.6	25.6	26.9	8.2
$[Pd(\mu\text{-}OH)(dppe)]_2^{2+}$ + dppe (49.2 μmol)	96.7	21.3	22.8	2.6
$[Pd(\mu\text{-}OH)(dppe)]_2^{2+}$ + dppe (65.6 μmol)	125.5	14.4	12.2	1.5
$[Pd(\mu\text{-}OH)(dppe)]_2^{2+}$ + dppe (98.4 μmol)	171.2	2.3	8.7	1.2

[a] The reactions were carried out in a sealed glass tube containing Na_2PdCl_4 or $[Pd(\mu\text{-}OH)(dppe)]_2^{2+}$ (16.4 μmol), diethyl maleate (3.1 mmol), water (56 mmol), and THF (3 mL). The mixture was stirred at 140 °C for 30 h. The mol ratios of the products (turnover number) are based on the number of moles of product formed per mol of catalyst used. [b] To the reaction mixture has been added $CuCl_2$ (33 μmol). In addition to the above products, this reaction also gave diethyl oxaloacetate (17 mol). [c] The quantity of the tertiary phosphine is 82 μmol.

Table IV. Conversion of Diethyl Maleate into Diethyl Fumarate in Presence of Tertiary Phosphines[a]

tertiary phosphine	conversion, %[b]
triphenylphosphine	85
tricyclohexylphosphine	97
1,2-bis(diphenylphosphino)ethane (dppe)	93
diphenylmethylphosphine	97
sodium 2-(diphenylphosphino)ethanesulfonate	10
disodium 2-(diphenylphosphino)ethanephosphonate	8
o-(diphenylphosphino)-*N*,*N*′-dimethylaniline	28

[a] The reactions were carried out in a sealed glass tube containing diethyl maleate (3.1 mmol), water (56 mmol), and the tertiary phosphine (0.16 mmol). The tube was heated at 120 °C for 30 h. [b] The percentage conversion was measured by GC–MS.

The catalyzed hydration of other alkenes such as sodium styrene-4-sulfonate, *trans*-ethyl crotonate, methyl acrylate, and 1-octene have been investigated under the same conditions in the presence of $[Pd(\mu\text{-}OH)(L\text{-}L)]_2^{2+}$. In no case did we observe the formation of alcohols. For the water soluble alkene, sodium styrene-4-sulfonate, and the hydrophobic alkenes, *trans*-ethyl crotonate and methyl acrylate, polymerization is observed. For 1-octene, isomerization to internal isomers occurs.

Tertiary Phosphine Catalyzed Isomerization of Diethyl Maleate to Diethyl Malate. The observed formation of diethyl fumarate from diethyl maleate under a number of different experimental conditions with added tertiary phosphines suggests that these compounds are acting as catalysts for this isomerization reaction. We have therefore tested this premise. Our results show that *cis–trans* isomerization from diethyl maleate to diethyl fumarate occurs in aqueous solution in the presence of catalytic quantities of tertiary phosphines. As examples, over 80% conversion of the *trans* isomer diethyl fumarate is obtained from diethyl maleate after a 30-h reaction at 120 °C when triphenylphosphine, tricyclohexylphosphine, 1,2-bis(diphenylphosphino)ethane, or diphenylmethylphosphine is present in the reaction. By contrast, less than 30% of diethyl fumarate is formed from diethyl maleate when *o*-(diphenylphosphino)-*N*,*N*′-dimethylaniline, sodium 2-(diphenylphosphino)ethanesulfonate, or disodium [2-(diphenylphosphino)ethyl]phosphonate are present (Table IV). Our results for the tertiary phosphine catalyzed reaction of diethyl maleate appear to contradict earlier work because previous workers have reported that the isomerization of dialkyl maleate to dialkyl fumarate does not occur in the presence of PPh_3.[14] The major difference in the two studies, however, is that our work is being carried out in aqueous THF solution, whereas the previous work was carried out in toluene solution.

Discussion

Catalytic Hydration of Diethyl Maleate. Our results for the $[Pd(\mu\text{-}OH)(L\text{-}L)]_2^{2+}$ catalyzed hydration of the carbon–carbon double bond in diethyl maleate are consistent with the reaction being catalyzed homogeneously by a palladium complex, and not heterogeneously by palladium metal. The failure to observe the catalyzed hydration of the carbon–carbon double bond in diethyl fumarate is supportive of a mechanism for the hydration of diethyl maleate that involves prior coordination of the alkene to the palladium center. The failure to observe catalyzed hydration in the presence of the complexes $[Pd(\mu\text{-}OH)L_2]_2^{2+}$ (L = PPh_3, PPh_2Me) with monodentate phosphines is likely due to the lower stability of these complexes as compared to the chelate complexes $[Pd(\mu\text{-}OH)(L\text{-}L)]_2^{2+}$. The data at different solution pH values show that the catalytic conversion is at a maximum at a pH value that is close to neutral.

The formation of an alcohol in the reaction of an alkene with water catalyzed by a mixture of $PdCl_4^{2-}$ and $CuCl_2$ is a transformation that has not been previously observed. The mass spectral data confirm that the same product, diethyl malate, is formed from diethyl maleate with both $[Pd(\mu\text{-}OH)(dppe)]_2^{2+}$ and the mixture of $PdCl_4^{2-}$ and $CuCl_2$ as catalyst. The deuterium labeling experiments confirm the formation of diethyl dideuteriomalate, with each deuterium coming from D_2O. Even though both catalyzed reactions containing either the μ-hydroxy complexes $[Pd(\mu\text{-}OH)(L\text{-}L)]_2^{2+}$ or the mixture of $PdCl_4^{2-}$ and $CuCl_2$ give the same product alcohol, it does not appear that the two systems in solution convert into the same catalytically active complex. This premise is supported by the observation that the conversion of diethyl maleate into diethyl malate is not increased by the addition of cupric ion to the solution, but for the catalyst system containing $PdCl_4^{2-}$ it is necessary to add Cu^{2+}, otherwise the conversion to diethyl malate is decreased. A further difference between the two catalysts is the formation of the oxidation product diethyl oxaloacetate only with the mixture of $PdCl_4^{2-}$ and $CuCl_2$.

The most reasonable mechanistic explanation of our results is that for each catalytic system an intermediate

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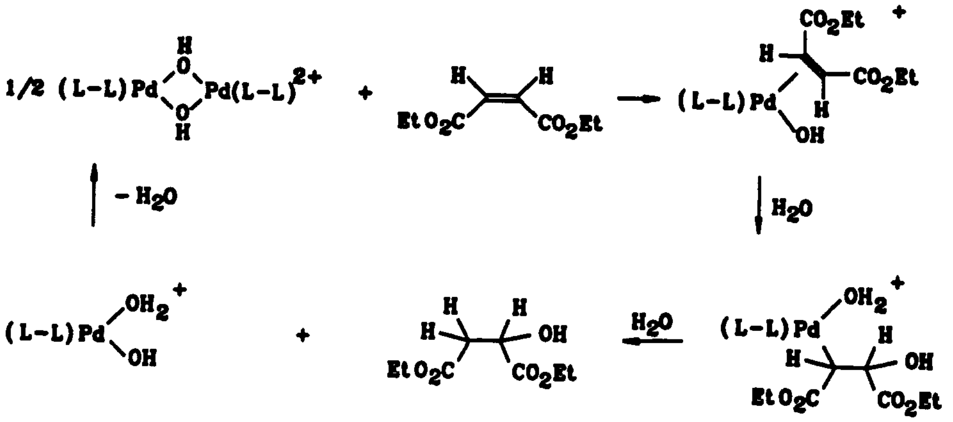
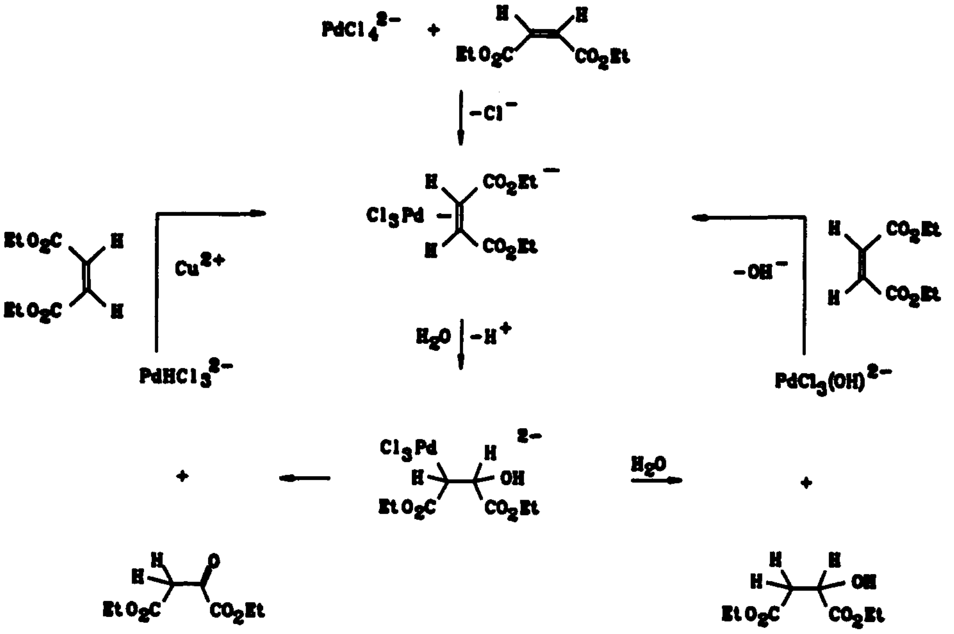
[14] Hiraki, K.; Ochi, N.; Takaya, H.; Fuchita, Y.; Shimokaura, Y.; Hayashida, H. *J. Chem. Soc., Dalton Trans.* **1990**, 1679.

Scheme I



Scheme II



alkylpalladium(II) complex is formed, and that this intermediate undergoes protonolytic cleavage before it undergoes β-hydrogen transfer to give the oxidation product, diethyl oxaloacetate. Such a protonolysis mechanism resembles that found in the reactions of alkene and alkyne organomercurials.[3] For the complex $[Pd(\mu\text{-}OH)(L\text{-}L)]_2^{2+}$, a plausible pathway is shown in Scheme I. In this scheme the intermediate alkyl complex is formed either by insertion of the alkene into the Pd–OH bond or by nucleophilic attack by water at the complexed alkene. The inhibition of the catalytic reaction by the addition of either acid or base can be explained by such a pathway. The addition of acid results in protonation of the Pd–OH bond, and the addition of base retards the protonolysis of the palladium alkyl bond.

For the reaction catalyzed by a mixture of $PdCl_4^{2-}$ and $CuCl_2$, the analogous pathway shown in Scheme II explains our results. Again, if protonolytic cleavage of the palladium alkyl bond occurs before β-hydrogen transfer, the product will be the alcohol, diethyl malate, rather than the keto ester, diethyl oxaloacetate. The formation of ketones by the catalyzed reaction of water with 1,2-disubstituted alkenes in the presence of a mixture of $PdCl_4^{2-}$ and $CuCl_2$ is, however, a slow reaction, and our catalyzed reactions with $[Pd(\mu\text{-}OH)(L\text{-}L)]_2^{2+}$ and with $PdCl_4^{2-}/Cu^{2+}$ more closely resemble the metal catalyzed hydration of alkynes.[15]

Our catalyzed hydration reaction with diethyl maleate to give diethyl malate is therefore due to two factors. The first of these is that the Wacker catalyzed oxidation of 1,2-disubstituted alkenes is slow, and the second of these is that the metal–alkyl bond is stabilized by the presence electron-withdrawing substituents on the α-carbon.[16] As a consequence, the alkylpalladium(II) intermediate $Pd(CH(CO_2Et)CH(OH)CO_2Et)H_2O(L\text{-}L)^+$ will have a sufficiently long lifetime that it can undergo hydrolytic cleavage with water before it undergoes β-hydrogen transfer leading to the ketone.[17,18]

The reaction between diethyl maleate and water catalyzed by a mixture of $PdCl_4^{2-}$ and $CuCl_2$ is summarized by the sequence shown in Scheme II. In this scheme the key intermediate is again the alkyl complex $PdCl_3(CH(CO_2Et)CH(OH)CO_2Et)^{2-}$. In this case, however,

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[15] Solomons, T. W. G. *Organic Chemistry*; Wiley: New York, 1984; pp 373–4.

[16] Elschenbroich, Ch.; Salzer, A. *Organometallics*; VCH: Weinheim, 1989; p 204.

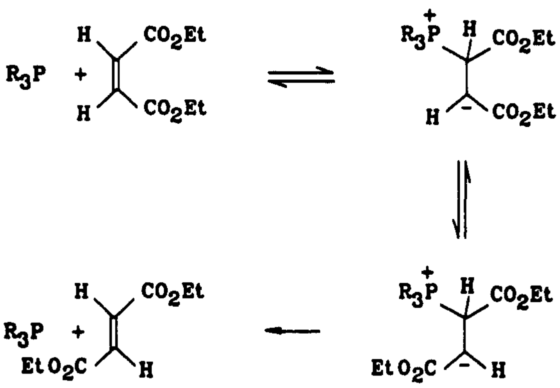
[17] For a precedent to this reaction see: Hosokawa, T.; Shinohara, T.; Ooka, Y.; Murahashi, S.-I. *Chem. Lett.* **1989**, 2001.

[18] When diethyl malate is reacted with the catalyst system instead of diethyl maleate, no diethyl oxaloacetate is detected in the product mixture. Nevertheless, the presence of considerable quantities of the ester hydrolysis products makes it impossible to exclude the possibility that at least some of the diethyl oxaloacetate is formed by oxidation of diethyl malate.

there is a parallel pathway that leads to the formation of the oxidation product of diethyl maleate, diethyl oxaloacetate. This product results from a β-hydrogen transfer reaction of $PdCl_3(CH(CO_2Et)CH(OH)CO_2Et)^{2-}$ to give the palladium(II) complexed vinyl alcohol, which rearranges to the keto ester, diethyl oxaloacetate. Apparently, the anionic alkyl complex $PdCl_3(CH(CO_2Et)CH(OH)CO_2Et)^{2-}$ is less stabilized against β-hydride transfer than is the cationic alkyl complex $Pd(CH(CO_2Et)CH(OH)CO_2Et)H_2O(L\text{-}L)^+$ with a chelating tertiary phosphine ligand.[19]

Several reasons can be offered to explain this observed stability difference between the two alkyl complexes. The β-hydride transfer step in a transition metal alkyl complex requires a vacant coordination position to be available on the metal center, and the cationic chelate complex $Pd(CH(CO_2Et)CH(OH)CO_2Et)H_2O(L\text{-}L)^+$ is less likely to dissociate a water molecule than is the anionic complex $PdCl_3(CH(CO_2Et)CH(OH)CO_2Et)^{2-}$ to lose a chloride ion.[20] A further possibility for the difference in stability is that a carbonyl group of one of the ester functionalities coordinates to palladium(II) in such a manner that the metal alkyl cannot readily achieve the necessary coplanarity for the β-hydrogen transfer reaction to occur.[21] Such a situation may be more significant for the cationic complex having a chelating L-L ligand because the steric bulk of the tertiary phosphine will be more restrictive to free rotation of the multiply substituted alkyl ligand, thereby increasing the barriers to adopting the preferred conformation.

Scheme III



Tertiary Phosphine Catalyzed Isomerization of Diethyl Maleate to Diethyl Malate. Our results show that the isomerization of diethyl maleate into diethyl fumarate in aqueous solution is catalyzed by tertiary phosphines (Table IV). As we noted in the Results of this paper, this observation appears to be in disagreement with an earlier report that triphenylphosphine does not cause the isomerization of diethyl maleate into diethyl fumarate.[14] Also we noted that an important difference between the two sets of results is that the work by Hiraki *et al.* was carried out in nonpolar organic solvents, and our work has been carried out in aqueous THF solution. The difference in reactivity in the two types of solvent can be explained on the basis of the reaction pathway shown in Scheme III. In this scheme a key intermediate is a phosphonium ylide. This ylide is a charged species, and such a zwitterion is expected to be solvated and stabilized by a donor solvent such as water that has a high dielectric constant. Although we have no direct evidence for the formation of such an intermediate, it is one that explains our results.[22] If an ylide is formed in the reaction between a tertiary phosphine and an electron deficient alkene, the presence of a carbon–carbon single bond in such an intermediate provides a pathway for rotation and the formation of the *trans* isomer.

Acknowledgment. We thank the Louisiana Educational Quality Support Fund, administered by the Louisiana Board of Regents, for support of this research. We thank Professor L. Hegedus for useful suggestions.

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[19] A stereochemical argument does not explain the relative reactivity of the two complexes. For $PdCl_3(CH(CO_2Et)CH(OH)CO_2Et)^{2-}$, the high *trans* effect of the alkyl ligand will favor loss of a chloride ion in a position *trans* to the alkyl. By contrast, for $Pd(CH(CO_2Et)CH(OH)CO_2Et)H_2O(L\text{-}L)^+$ it is the water ligand that will preferentially dissociate, leaving a vacant coordination site in a position *cis* to the alkyl ligand. A vacant *cis* coordination position is the preferred one for β-hydrogen transfer to occur, although the complex $Pd(CH(CO_2Et)CH(OH)CO_2Et)H_2O(L\text{-}L)^+$ is the least reactive for the β-hydrogen transfer reaction.

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