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New Insight into the Mechanism of Catalytic Hydrogenation Allows the Structure of the Key Intermediate in Asymmetric Hydrogenation to be Predicted

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Dedicated to Professor A. I. Scott on the occasion of his 70th birthday

Abstract: An approach has been developed to determine the regioselectivity of hydrometalation in homogeneous and heterogeneous hydrogenation of alkenes. By studying the electronic effects on the orientation of hydrometalation it is found with palladium and rhodium that this key step is a two electron process that can occur by two modes (**a** $Pd^{\delta+}$–$H^{\delta-}$ or **b** $Pd^{\delta-}$– $H^{\delta+}$). This provides valuable information about the structure of the metal-alkyl intermediate and helps rationalise how chiral induction occurs.

INTRODUCTION

Asymmetric hydrogenation of prochiral double bonds using chiral homogeneous catalysts is a major method for access to enantiomerically pure compounds.[1-4] The transfer of the chirality from the ligand to the product occurs during the addition of the metal hydrogen bond to the double bond (hydrometalation). The orientation of the metal when approaching the double bond is critical in determining the chirality of the product since it bears the chiral ligand. Great effort has been directed at elucidating the structure of the metal-alkyl complex formed by hydrometalation as it reveals the regiochemistry of this key step.[5-15] So far it has proved difficult to isolate the complexes with only a few being identified by NMR. It is highly desirable to develop a method that can determine the regioselectivity of hydrometalation with a wide range of catalysts and substrates so that a model can be constructed to analyse the induction of chirality during hydrometalation.

When a *cis*-alkene is hydrogenated some of the *trans*-isomer is formed by β-elimination from the metal-alkyl complex after rotation (Scheme 1). If deuterium gas is used then label is incorporated into one end of the double bond of the *trans*-alkene which reports that the metal must have been added to the other end of the double bond thus revealing the structure of the metal-alkyl complex. Using this strategy we have shown that hydrometalation may occur by mode **a** ($Pd^{\delta+}$– $H^{\delta-}$) or mode **b** ($Pd^{\delta-}$– $H^{\delta+}$) depending on the polarity of the substrate and the intrinsic electronic properties of the metal.[16-17]

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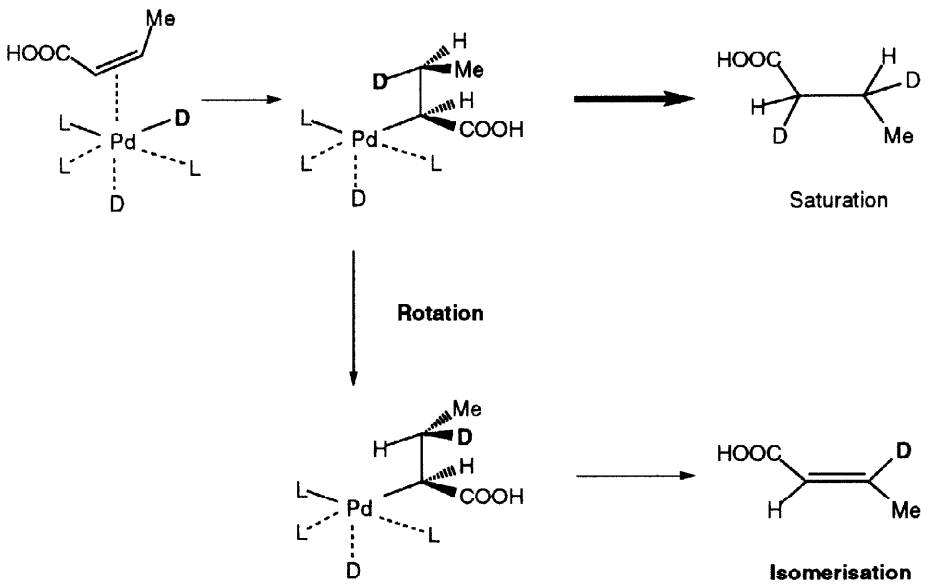
This suggests that the electronic environment of the double bond is a major factor in determining the regioselectivity of hydrometalation and therefore the structure of the metal-alkyl complex will be highly dependent on the polarity of the double bond.

Scheme 1



RESULTS AND DISCUSSION

It has been empirically found that the best substrates for asymmetric hydrogenation have functional groups conjugated to the double bond such as α, β-unsaturated carboxylic acids, styrenes and enol ester.[18] An explanation involving metal ligation to the functional groups has been suggested.[19-23] Using our new approach we have investigated the influence of the functional groups on the regioselectivity of hydrometalation with these substrates.[16-17]

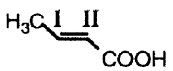
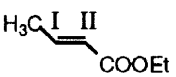
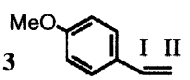
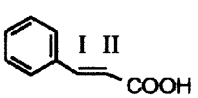
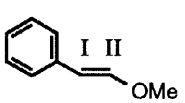
When crotonic acid is hydrogenated using deuterium and bis[1,2-bis(diphenyl phosphino)-ethane] palladium(0), deuterium is incorporated solely in the position remote to the carboxyl group of the isolated *trans*-isomer **1** (Table 1).

This identifies that the metal must add to the carbon that is adjacent to the carboxyl group. The regioselectivity could be due to the carboxyl group ligating to the palladium in the metal-alkyl complex to form a four membered ring. The methyl ester of crotonic acid **2** also shows the same labelling pattern suggesting that ligation is not a key factor in controlling hydrometalation. Instead, the polarity of the double bond imposed by the electron withdrawing carboxyl group induces the palladium hydrogen bond to add by mode **a** ($Pd^{\delta+}-H^{\delta-}$) in a similar fashion to Michael type addition of a nucleophile to α,β-unsaturated compounds.

The double bond in substrate **3** has the reverse polarity to that of crotonic acid as a result of conjugation to an aromatic ring. If hydropalladation occurs by mode **a** as it does for hydroboration it would be predicted that

deuterium would be added to the carbon of the double bond adjacent to the aromatic ring. The deuterium incorporation is found to be exclusively remote to the phenyl group which suggests that palladium and hydrogen add by mode **b** ($Pd^{\delta-} - H^{\delta+}$).

Table 1. Deuterium incorporation into *trans*-Alkenes using Homogeneous catalysts

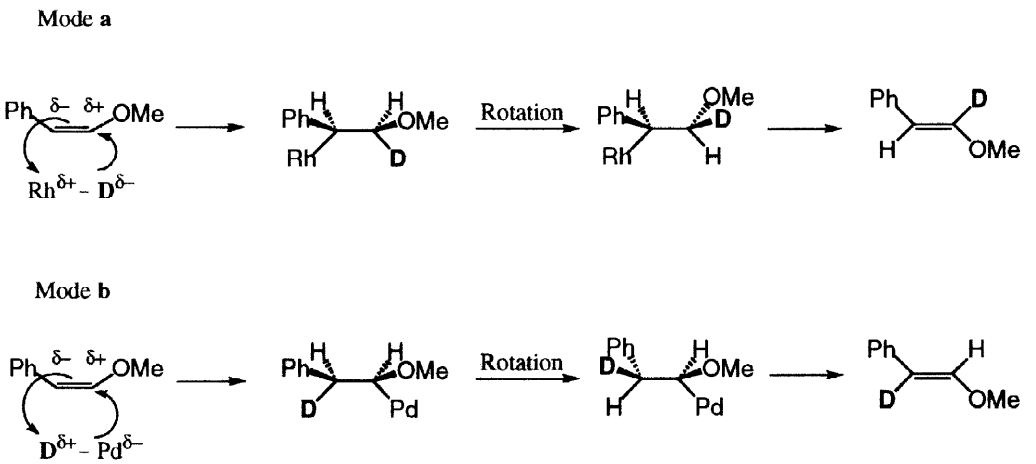
	Product	Catalyst [a]	Deuterium Distribution (%)		Relative Ratio of Deuterium (%)	
			I	II	I	II
1		Pd	64	0	100	0
2		Pd	59	0	100	0
3		Pd	0	*Cis* 32 [b] *Trans* 32	0	100
	" "	Rh	0	0	0	0
4		Pd	37	6	86	14
	" "	Rh	22	0	100	0
5		Pd	37	4	90	10
	" "	Rh	0	55	0	100

[a] Pd: bis[1,2-bis(diphenylphosphino)-ethane] palladium(0) and Rh: Chlorotris (triphenyl phosphine)-rhodium (I) (Wilkinson's catalyst). [b] *Cis/trans* refers to the deuterium being *cis/trans* to the aromatic group. Some compound was identified with 2 deuterium in the terminal position of the double bond. The proportion of this compound increased with a longer reaction time as did that of the mono-deuterated species.

When there are two functional groups conjugated to the double bond it is possible to establish which mode of hydrometalation is dominant. Isomerisation of cinnamic acid with bis[1,2-bis(diphenylphosphino)-ethane] palladium(0) and deuterium gas gives a mixture of addition by mode **a** and mode **b**. This flexibility of the palladium-hydrogen bond to add both ways round could be detrimental to enantioselectivity with similar

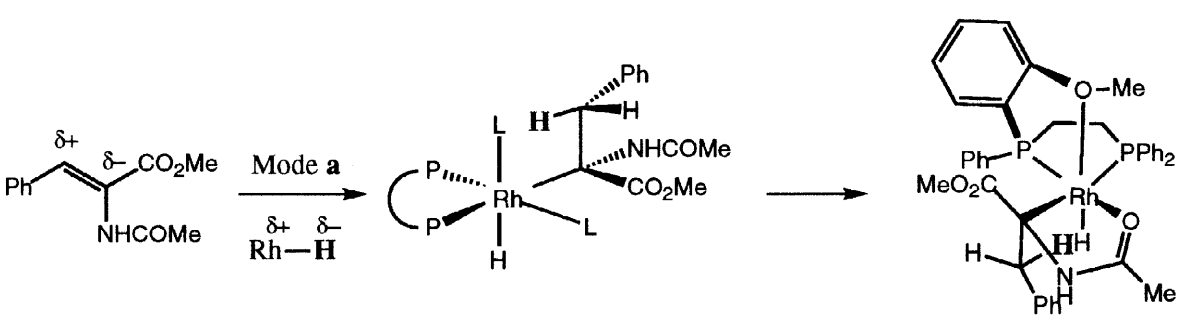
prochiral substrates. The metal-alkyl complexes formed by mode **a** and mode **b** differ from each other in chiral environment and could lead to the opposite enantioselectivity which would lower the ee for the asymmetric hydrogenation. Remarkably with the rhodium homogeneous catalyst [Chlorotris(triphenyl phosphine)-rhodium (I)] it is found that hydrometalation only occurs by mode **a** with cinnamic acid. This may explain why rhodium homogeneous catalysts have been found to be excellent for asymmetric hydrogenation because the rhodium hydrogen bond is less flexible and undergoes hydrometalation predominantly by mode **a**. This intrinsic difference in the electronic property of the metal-hydrogen bond is clearly illustrated with the enol ether **5** where palladium is shown to add exclusively by mode **b** while rhodium adds by mode **a** (Scheme 2).

Scheme 2



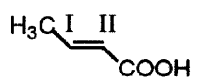
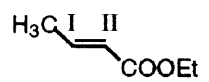
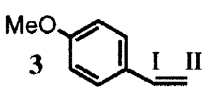
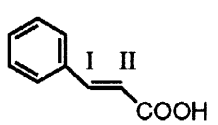
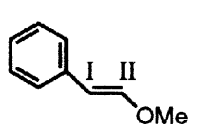
In the asymmetric reduction of (*Z*)-methyl α-acetamidocinnamate using a rhodium homogeneous catalyst the metal-alkyl complex has been identified by NMR.[14] The observed regioselectivity of hydrometalation is consistent with mode **a** as predicted by the new model (Scheme 3).

Scheme 3



Asymmetric heterogeneous hydrogenation has also attracted much attention in recent years.[24-31] The mechanism of induction of chirality has remained obscure partly owing to the difficulty in identifying active intermediates. Using the new approach the key step of hydrometalation can also be studied with heterogeneous catalysts which allows a direct comparison to be made with the better characterised homogeneous catalysts. The results of the hydrogenation of the five substrates using Pd/C and deuterium gas are shown in Table 2.

Table 2. Deuterium Incorporation into *trans*-Alkenes Using Pd/C

	Product	Deuterium Distribution (%) I	Deuterium Distribution (%) II	Relative Ratio of Deuterium (%) I	Relative Ratio of Deuterium (%) II
1		58	0	100	0
2		60	0	100	0
3		0	*Cis* 40 [a] *Trans* 40	0	100
4		29	30	49	51
5		56	1	98	2

[a] *Cis/trans* refers to the deuterium being *cis/trans* to the aromatic group. Some compound was identified with 2 deuterium in the terminal position of the double bond. The proportion of this compound increased with a longer reaction time as did that of the mono-deuterated species.

Regioselectivity of deuterium incorporation reveals that hydrometalation on the metal surface occurs in a similar manner to the homogeneous system. When there is solely an electron withdrawing group conjugated to double bond, compounds **1** and **2**, hydrometalation occurs only by mode **a** ($Pd^{\delta+} - H^{\delta-}$) as it does with the

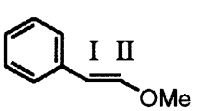
homogeneous palladium catalyst (Table 1 and 2). Likewise, with an electron donating substituent conjugated to the double bond hydrometalation occurs by mode **b** ($Pd^{\delta-} - H^{\delta+}$) (compound **3**, Table 1 and 2). The difunctional alkenes **4** and **5** are a much more sensitive assay for the electronic nature of the metal-hydrogen bond as they can accommodate both modes of addition. The results show that mode **a** is enhanced with the homogeneous palladium catalyst compared to Pd/C. This shift to mode **a** with the homogeneous palladium catalyst could be due to the stabilisation of the electron deficient palladium centre in mode **a** ($Pd^{\delta+} - H^{\delta-}$) by the electron donating phosphine ligands. Tuning the electronic properties of the ligand could potentially shift the regioselectivity of hydrometalation to favour chiral induction by fixing hydrometalation to occur by solely mode **a** or mode **b**.

The promotion of mode **a** by electron donating ligands in homogeneous palladium catalysts led us to investigate whether similar ligands could modify the electronic properties of heterogeneous palladium catalysts.[32] Quinoline and triphenylphosphine are found to enhance mode **a** in a concentration dependent manner (Table 3). Interestingly, cinchonidine which possesses a quinoline moiety has been found, so far, to be the most successful modifier for heterogeneous asymmetric hydrogenation.[19-20]

Table 3. Effect of Quinoline and Triphenylphosphine on the Mode of Hydrometalation[a]

Ligand	Concentration (mM)	Deuterium Distribution (%)		Relative Ratio of Deuterium (%)	
		I	II	I	II
Quinoline	0	56	1	98	2
	50	50	19	72	28
	100	36	27	57	43
	150	36	27	57	43
Triphenyl phosphine	25	30	22	58	42

[a] Hydrogenation was carried out using *cis*-isomer of compound **5** as the substrate:



In conclusion a new approach has been developed to determine the regioselectivity of hydrometalation which reports the structure of the metal-alkyl intermediate. The results are consistent with two modes of addition (**a** $Pd^{\delta+} - H^{\delta-}$ or **b** $Pd^{\delta-} - H^{\delta+}$) that take place with palladium and rhodium by a two electron mechanism. The identification that the electronic property of the catalyst has a strong influence on the regioselectivity of hydrometalation should facilitate the rationalisation of chiral induction in asymmetric hydrogenation.

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EXPERIMENTAL

Materials. The *cis*-isomers of **1**, **2** and **4** were prepared by reduction of corresponding acetylenes over Lindlar Catalyst and purified by preparative TLC (Jacobsen, E.N.; Deng, L.; Furukawa, Y.; Martinez, L.E. Tetrahedron, **1994**, 50, 4331). The *cis*-isomer of **5** was purchased from Aldrich and further purified by preparative TLC. Bis[1,2-bis(diphenylphosphino)-ethane] palladium (0), tris(triphenylphosphine)-rhodium(I)chloride, palladium on charcoal (10%), Lindlar catalyst (5%) and deuterium gas were purchased from Aldrich. C_2H_5OD and benzene were purchased from Aldrich and dried over 4Å molecular sieves.

Measurement of Deuterium Incorporation. Deuterium incorporation was measured by integration of the respective ^1H NMR signals: (1) when only one position of the double bond was exchanged by deuterium (substrates **1**, **2** and **3**), the amount of deuterium incorporated was calculated by referring to a full proton on the other position of the double bond. (2) When both positions of the double bond were exchanged by deuterium, the calculation was made by referring to another group within the molecule as an internal standard (**4** ,**5**). Errors for the data are +/- 5%.

Homogeneous Hydrogenation

***trans*-Crotonic acid (1):** To a solution of *cis*-isomer of **1** (86 mg, 1 mmol) in 3 ml benzene was added 68 mg bis[1,2-bis(diphenylphosphino)-ethane] palladium (0). The mixture was degassed and refilled with D_2 through a balloon. The reaction mixture was stirred for 80 min at room temperature under 1 atm of D_2. The reaction mixture was then washed through a silica gel column with ether and evaporated at 0°C to give the product residue (79 mg) which was determined by ^1H NMR to consist of a mixture of 46% reduced product , 12% *cis*-isomer and 42% **1**. The pure form of **1** was obtained by preparative TLC, eluting with ethyl acetate - petroleum ether - methanol (9 : 15 : 0.1), which was then evaporated to dryness at 0 °C and analysed by ^1H NMR (data for both labelled and unlabelled **1** is given) and MS. R_f = 0.23; ^1H NMR (250 MHz, $CDCl_3$) δ 7.08 (dq, J = 15.7, 7.2 Hz, 1 H), 5.83 (dq, J = 15.7, 1.5 Hz, 1 H), 5.82 (q, J = 1.5 Hz, 1 H), 1.90 (br, CH_3); HRMS (CI) m/z (M^+) calcd for $C_4H_5{}^2HO_2$, 87.0431; found, 87.0430.

***trans*-Ethyl-crotonate (2)**: To a solution of *cis*-isomer of **2** (114 mg, 1 mmol) in 3 ml benzene was added 68 mg bis[1,2-bis(diphenylphosphino)-ethane] palladium (0). The mixture was degassed and refilled with D_2 through a balloon. The reaction mixture was stirred for 40 min at room temperature under 1 atm of D_2. The reaction mixture was then washed through a silica gel column with ether and evaporated at 0°C to give the product residue (109 mg) which was determined by ^1H NMR to consist of a mixture of 52% reduced product,

10% *cis*-isomer and 38% **2**. The pure form of **2** was obtained by preparative TLC, eluting with ether - hexane (1 : 15), which was then evaporated to dryness at 0°C and analysed by ^{1}H NMR (data for both labelled and unlabelled **2** is given) and MS. R_f = 0.22; ^{1}H NMR (250 MHz, $CDCl_3$) δ 6.96 (dq, J = 15.7, 7.1 Hz, 1 H), 5.83 (dq, J = 15.7, 1.7 Hz, 1 H), 5.82 (q, J = 1.7 Hz, 1 H), 4.16 (q, J = 7.0 Hz, 2 H), 1.88 (br, CH_3), 1.26 (t, J = 7.0 Hz); HRMS (CI) m/z (M^+) calcd for $C_6H_9{}^2HO_2$, 115.0744; found, 115.0738.

4-Methoxystyrene (3): To a solution of **3** (134 mg, 1 mmol) in 3 ml benzene was added 68 mg bis[1,2-bis(diphenylphosphino)-ethane] palladium (0). The mixture was degassed and refilled with D_2 through a balloon. The reaction mixture was stirred for 15 min at room temperature under 1 atm of D_2. The reaction mixture was then washed through a silica gel column with ether and evaporated at 0°C to give the product residue (118 mg) which was determined by ^{1}H NMR to consist of a mixture of 85% reduced product and 15% **3**. ^{1}H NMR (250 MHz, $CDCl_3$) δ 7.35, 6.85 (aromatic), 6.65 (m, 1 H), 5.62 (d, J = 17.6 Hz, 1 H), 5.61 (d, J = 17.6 Hz, 1H), 5.13 (d, J = 11.1 Hz, 1 H), 5.12 (d, J = 11.1 Hz, 1 H), 3.76 (s, OCH_3). HRMS (CI) m/z (M^+) calcd for $C_9H_9{}^2HO$, 135.0795; found, 135.0765.

4-Methoxystyrene (3): To a solution of **3** (134 mg, 1 mmol) in 3 ml benzene was added 70 mg tris(triphenylphosphine)-rhodium(I)chloride. The mixture was degassed and refilled with D_2 through a balloon. The reaction mixture was stirred for 30 min at room temperature under 1 atm of D_2. The reaction mixture was then washed through a silica gel column with ether and evaporated at 0°C to give the product residue (129 mg) which was determined by ^{1}H NMR to consist of a mixture of 33% reduced product and 66% **3**. ^{1}H NMR (250 MHz, $CDCl_3$) δ 7.35, 6.85 (aromatic), 6.65 (dd, J = 17.6, 11.1 Hz, 1 H), 5.62 (d, J = 17.6 Hz, 1 H), 5.13 (d, J = 11.1 Hz, 1 H), 3.76 (s, OCH_3). HRMS (CI) m/z (M^+) calcd for $C_9H_9{}^2HO$, 135.0795; found, 135.0786.

***trans*-Cinnamic acid (4):** To a solution of *cis*-isomer of **4** (148 mg, 1 mmol) in 3 ml benzene was added 68 mg bis[1,2-bis(diphenylphosphino)-ethane] palladium (0). The mixture was degassed and refilled with D_2 through a balloon. The reaction mixture was stirred for 30 min at room temperature under 1 atm of D_2. The reaction mixture was then washed through a silica gel column with ether and evaporated at 0°C to give the product residue (145 mg) which was determined by ^{1}H NMR to consist of a mixture of 91% reduced product and 9% **4**. The pure form of **4** was obtained by preparative TLC, eluting with ethyl acetate-hexane-methanol (100 : 30 : 0.5), which was then evaporated to dryness and analysed by ^{1}H NMR (data for both labelled and unlabelled **4** is given) and MS. R_f = 0.28; ^{1}H NMR (250 MHz, $CDCl_3$) δ 7.79 (d, J = 16.1 Hz, 1H), 7.78 (br, 1 H), 7.65 - 7.15 (aromatic), 6.45 (d, J = 16.1 Hz, 1 H), 6.44 (br, 1 H). HRMS (CI) m/z (M^+ - H) calcd for $C_9H_6{}^2HO_2$, 148.0509; found, 148.0518.

***trans*-Cinnamic acid (4):** To a solution of *cis*-isomer of **4** (148 mg, 1 mmol) in 3 ml benzene was added 70 mg tris(triphenylphosphine)-rhodium(I)chloride. The mixture was degassed and refilled with D_2 through a balloon. The reaction mixture was stirred for 5 hrs at room temperature under 1 atm of D_2. The reaction mixture was then washed through a silica gel column with ether and evaporated at 0°C to give the product residue (145 mg) which was determined by ^{1}H NMR to consist of a mixture of 89% reduced product and 11% **4**. The pure form of **4** was obtained by preparative TLC, eluting with ethyl acetate-hexane-methanol (100 : 30

: 0.5), which was then evaporated to dryness and analysed by ^1H NMR (data for both labelled and unlabelled **4** is given) and MS. R_f = 0.16; ^1H NMR (250 MHz, $CDCl_3$) δ 7.79 (d, J = 16.1 Hz, 1H), 7.65 - 7.15 (aromatic), 6.45 (d, J = 16.1 Hz, 1 H), 6.44 (br, 1 H). HRMS (CI) m/z (M^+ - H) calcd for $C_9H_6{}^2HO_2$, 148.0509; found, 148.0512.

***trans*-β-Methoxystyrene (5)**: To a solution of *cis*-isomer of **5** (134 mg, 1 mmol) in 3 ml benzene was added 68 mg bis[1,2-bis(diphenylphosphino)-ethane] palladium (0). The mixture was degassed and refilled with D_2 through a balloon. The reaction mixture was stirred for 40 min at room temperature under 1 atm of D_2. The reaction mixture was then washed through a silica gel column with ether and evaporated at 0°C to give the product residue (179 mg) which was determined by ^1H NMR to consist of a mixture of 26% reduced product, 62% *cis*-isomer and 12% **5**. The pure form of **5** was obtained by preparative TLC, eluting with hexane, which was then evaporated to dryness and analysed by ^1H NMR (data for both labelled and unlabled **5** is given) and MS. R_f = 0.10; ^1H NMR (250 MHz, $CDCl_3$) δ 7.60, 7.30, 7.15 (aromatic), 7.06 (d, J = 13.0 Hz, 1 H), 7.06 (t, J = 3.5 Hz, 1 H), 5.83 (d, J = 13.0 Hz, 1 H), 5.81 (t, J = 3.5 Hz, 1 H), 3.72 (s, OCH_3). HRMS (CI) m/z (M^+) calcd for $C_9H_9{}^2HO$, 135.0795; found, 135.0800.

***trans*-β-Methoxystyrene (5)**: To a solution of *cis*-isomer of **5** (134 mg, 1 mmol) in 3 ml benzene was added 70 mg tris(triphenylphosphine)-rhodium(I)chloride. The mixture was degassed and refilled with D_2 through a balloon. The reaction mixture was stirred for 40 min at room temperature under 1 atm of D_2. The reaction mixture was then washed through a silica gel column with ether and evaporated at 0°C to give the product residue (179 mg) which was determined by ^1H NMR to consist of a mixture of 59% reduced product, 24% *cis*-isomer and 17% **5**. The pure form of **5** was obtained by preparative TLC, eluting with hexane, which was then evaporated to dryness and analysed by ^1H NMR (data for both labelled and unlabelled **5** is given) and MS. R_f = 0.10; ^1H NMR (250 MHz, $CDCl_3$) δ 7.60, 7.30, 7.15 (aromatic), 7.06 (d, J = 13.0 Hz, 1 H), 5.83 (d, J = 13.0 Hz, 1 H), 5.81 (t, J = 3.5 Hz, 1 H), 3.72 (s, OCH_3). HRMS (CI) m/z (M^+) calcd for $C_9H_9{}^2HO$, 135.0795; found, 135.0789.

Heterogeneous Hydrogenation

***trans*-Crotonic acid (1)**: To a solution of *cis*-isomer of **1** (86 mg, 1 mmol) in 3 ml C_2H_5OD was added 3 mg of Pd/C (10%). The mixture was degassed and refilled with D_2 through a balloon. The reaction mixture was stirred for 10 min at room temperature under 1 atm of D_2. The reaction mixture was stirred for 8 min at room temperature under 1 atm of D_2. The reaction mixture was then filtered to remove the catalyst and evaporated at 0 °C to give the product residue (81 mg) which was determined by ^1H NMR to consist of a mixture of 12% *cis*-isomer, 45% reduced product and 43% **1**. The pure form of **1** was obtained by preparative TLC, eluting with ethyl acetate - petroleum ether - methanol (9 : 15 : 0.1), which was then evaporated to dryness at 0°C and analysed by ^1H NMR (data for both labelled and unlabelled **1** is given) and MS. R_f = 0.23; ^1H NMR (250 MHz, $CDCl_3$) δ 7.08 (dq, J = 15.7, 7.2 Hz, 1 H), 5.83 (dq, J = 15.7, 1.5 Hz, 1 H), 5.82 (q, J = 1.5 Hz, 1 H), 1.90 (br, CH_3); HRMS (CI) m/z (M^+) calcd for $C_4H_5{}^2HO_2$, 87.0431; found, 87.0428.

***trans*-Ethyl-crotonate (2)**: To a solution of *cis*-isomer of **2** (114 mg, 1 mmol) in 3 ml C_2H_5OD was added 3 mg of Pd/C (10%). The mixture was degassed and refilled with D_2 through a balloon. The reaction mixture was stirred for 10 min at room temperature under 1 atm of D_2. The reaction mixture was then filtered to remove the catalyst and evaporated at 0°C to give the product residue (109 mg) which was determined by ^1H NMR to consist of a mixture of 52% reduced product, 6% *cis*-isomer and 42% **2**. The pure form of **2** was obtained by preparative TLC, eluting with ether - hexane (1 : 15), which was then evaporated to dryness at 0 °C and analysed by ^1H NMR (data for both labelled and unlabelled **2** is given) and MS. $R_f = 0.22$; ^1H NMR (250 MHz, $CDCl_3$) δ 6.96 (dq, J = 15.7, 7.1 Hz, 1 H), 5.83 (dq, J = 15.7, 1.7 Hz, 1 H), 5.82 (q, J = 1.7 Hz, 1 H), 4.16 (q, J = 7.0 Hz, 2 H), 1.88 (br, CH_3), 1.26 (t, J = 7.0 Hz); HRMS (CI) m/z (M^+) calcd for $C_6H_9{}^2HO_2$, 115.0744; found, 115.0738.

4-Methoxystyrene (3): To a solution **3** (134 mg, 1 mmol) in 3 ml C_2H_5OD was added 3 mg of Pd/C (10%). The mixture was degassed and refilled with D_2 through a balloon. The reaction mixture was stirred for 25 min at room temperature under 1 atm of D_2. The reaction mixture was then filtered to remove the catalyst and evaporated at 0°C to give the product residue (122 mg) which was determined by ^1H NMR to consist of a mixture of 90% reduced product and 10% **3**. ^1H NMR (250 MHz, $CDCl_3$) δ 7.35, 6.85 (aromatic), 6.65 (m, 1 H), 5.62 (d, J = 17.6 Hz, 1 H), 5.61 (d, J = 17.6 Hz, 1H), 5.13 (d, J = 11.1 Hz, 1 H), 5.12 (d, J = 11.1 Hz, 1 H), 3.76 (s, OCH_3). HRMS (CI) m/z (M^+) calcd for $C_9H_9{}^2HO$, 135.0795; found, 135.0785.

***trans*-Cinnamic acid (4)**: To a solution of *cis*-isomer of **4** (148 mg, 1 mmol) in 3 ml C_2H_5OD was added 3 mg of Pd/C (10%).The mixture was degassed and refilled with D_2 through a balloon. The reaction mixture was stirred for 50 min at room temperature under 1 atm of D_2. The reaction mixture was then filtered to remove the catalyst and evaporated at 0°C to give the product residue (142 mg) which was determined by ^1H NMR to consist of a mixture of 15% cis-isomer, 80% reduced product and 5% **4**. The pure form of **4** was obtained by preparative TLC, eluting with ethyl acetate-hexane-methanol (100 : 30 : 0.5), which was then evaporated to dryness and analysed by ^1H NMR (data for both labelled and unlabelled **3** is given) and MS. R_f = 0.28; ^1H NMR (250 MHz, $CDCl_3$) δ 7.79 (d, J = 16.1 Hz, 1H), 7.78 (br, 1 H), 7.65 - 7.15 (aromatic), 6.45 (d, J = 16.1 Hz, 1 H), 6.44 (br, 1 H). HRMS (CI) m/z (M^+ - H) calcd for $C_9H_6{}^2HO_2$, 148.0509; found, 148.0520.

***trans*-β-Methoxystyrene (5)**: To a solution of *cis*-isomer of **5** (134 mg, 1 mmol) in 3 ml benzene was added 3 mg of Pd/C (10%). The mixture was degassed and refilled with D_2 through a balloon. The reaction mixture was stirred for 45 min at room temperature under 1 atm of D_2. The reaction mixture was then filtered to remove the catalyst and evaporated at 0°C to give the product residue (129 mg) which was determined by ^1H NMR to consist of a mixture of 12% *cis*-isomer, 80% reduced product and 8% **5**. The pure form of **5** was obtained by preparative TLC, eluting with hexane, which was then evaporated to dryness and analysed by ^1H NMR (data for both labelled and unlabled **5** is given) and MS. $R_f = 0.10$; ^1H NMR (250 MHz, $CDCl_3$) δ 7.60, 7.30, 7.15 (aromatic), 7.06 (d, J = 13.0 Hz, 1 H), 7.06 (t, J = 3.5 Hz, 1 H), 5.83 (d, J = 13.0 Hz, 1 H), 5.81 (t, J = 3.5 Hz, 1 H), 3.72 (s, OCH_3). HRMS (CI) m/z (M^+) calcd for $C_9H_9{}^2HO$, 135.0795; found, 135.0806.

Typical procedure for the addition of electron donating ligands into heterogeneous system

Quinoline: To a solution of *cis*-isomer (134 mg, 1 mmol) in 3 ml of benzene was added 20 mg 10% Pd-C and 39 mg of quinoline(0.3 mmol). The mixture was degassed and refilled with D_2 through a balloon. The reaction mixture was stirred for 2 h at room temperature under 1 atm of D_2 followed by removal of the catalyst by filtration. The filtrate was evaporated to give a mixture of quinoline and the product (162 mg) which was determined by ^1H NMR to consist of 40% reduced product , 48% *cis*-isomer and 12% *trans*-isomer. The pure form of the *trans*-isomer was obtained by column chromatography eluting with hexane and the incorporation of the deuterium at each position on the double bond was determined by integration of the respective ^1H NMR signals, using the methyl group as an internal standard. For the experiment performed using 100mM quinoline samples were taken over the whole course of the reaction. The deuterium distribution across the double bond was found not to vary with reaction time.

Triphenylphosphine: To a solution of *cis*-isomer of **5** (134 mg, 1 mmol) in 3 ml of benzene was added 20 mg 10% Pd-C and 20 mg of triphenylphosphine (0.08 mmol). The mixture was degassed and refilled with D_2 through a balloon. The reaction mixture was stirred for 2 h at room temperature under 1 atm of D_2 followed by removal of the catalyst by filtration. The filtrate was evaporated to give a mixture of triphenylphosphine and the product (146 mg) which was determined by ^1H NMR to consist of 40% reduced product , 50% *cis*-isomer and 10% *trans*-isomer. The pure form of the *trans*-isomer was obtained by column chromatography eluting with hexane and the incorporation of the deuterium at each position on the double bond was determined by integration of the respective ^1H NMR signals, using the methyl group as an internal standard.

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