Discovery that quinoline and triphenylphosphine alter the electronic properties of hydrogenation catalysts

Jinquan Yu and Jonathan B. Spencer*†

University Chemical Laboratory, Lensfield Road, Cambridge, UK CB2 1EW

Quinoline and triphenylphosphine are found to influence the polarisation of the palladium–hydrogen bond in heterogeneous hydrogenation; this provides a possible explanation for why the addition of these compounds increases the selectivity of the semi- reduction of alkynes.

The selective reduction of alkynes to *cis*-alkenes using heterogeneous catalysts, such as palladium on carbon, is a key reaction in organic chemistry.[1,2] Quinoline and triphenylphosphine have been widely used as additives in heterogeneous hydrogenation to improve the selectivity of this reaction.[3] There has been great interest in rationalising how these compounds alter the properties of the palladium to achieve superior selectivity. Several theories have been put forward, including the selective blocking of sites that cause the side reactions and promoting the rearrangement of the surface structure.[4–6] It has not been possible, however, to probe whether quinoline and triphenylphosphine, both potentially strong ligands, could alter the electronic properties of the metal catalyst. Recently we have devised an approach to achieve this by determining which electronic mode [mode (*a*) M$^{\delta+}$–H$^{\delta-}$ or (*b*) M$^{\delta-}$–H$^{\delta+}$, Scheme 1] of hydrometalation is promoted by the catalyst.[7,8]

EWG = electron-withdrawing group
EDG = electron-donating group

Scheme 1

When *cis*-enol ether **1** is isomerised to the *trans*-isomer **2** using deuterium and palladium on carbon the location of the deuterium on the double bond reports which mode of hydrometalation takes place (Scheme 2). The result with unmodified palladium on carbon (Fig. 1) is that the deuterium is incorporated almost entirely at position I, which shows that mode (*b*) (M$^{\delta-}$–H$^{\delta+}$) is dominant; this is a consequence of the polarisation of the palladium–hydrogen bond being induced by the electronic dipole of the substrate.[7,8] Remarkably, when this reaction is carried out in the presence of quinoline, mode (*a*) (M$^{\delta+}$–H$^{\delta-}$) is significantly enhanced (Fig. 1). This suggests that the quinoline, being a strong electron-donating ligand, is capable of stabilising the electron-deficient metal centre in mode (*a*) (M$^{\delta+}$–H$^{\delta-}$). The enhancement of mode (*a*) is found to be dependent on the concentration of quinoline (Table 1). No further enhancement of mode (*a*) occurs when the quinoline concentration is increased above 100 mM, suggesting saturation of the surface by quinoline at this concentration.

The same experiment has been carried out with triphenylphosphine, another electron-donating ligand, and this is found also to promote mode (*a*) (M$^{\delta+}$–H$^{\delta-}$) to a similar extent (Table 1). These results prompted us to propose an explanation for origin of the selectivity of these catalysts for triple bonds over

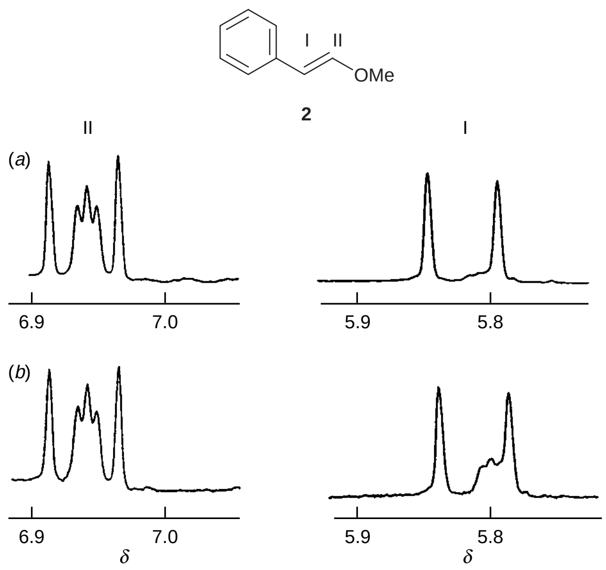
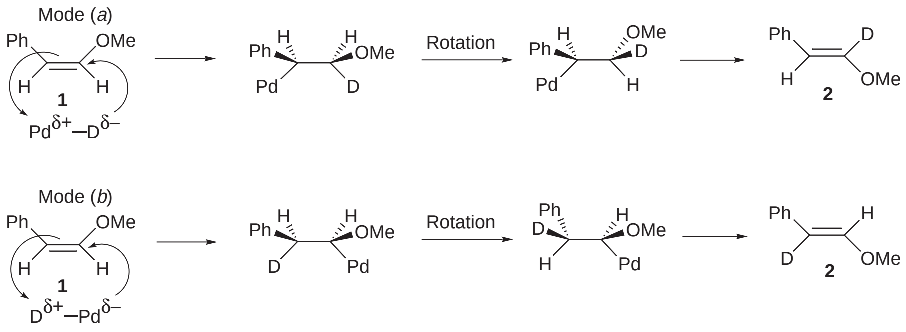


Fig. 1 Part of the ^{1}H NMR spectrum (250 MHz) (double bond region) for compound **2** (in CDCl$_3$) formed by the isomerization of the corresponding *cis*-isomer using D$_2$ and (*a*) Pd/C or (*b*) Pd/C with 50 mM quinoline. The triplets observed inside the doublets arise from deuterium hydrogen coupling in the labelled compound.



Scheme 2

Table 1 Dependance of reaction mode on ligand[a]

Ligand	Concen-tration (mM)	Deuterium distribution[b] (%)		Relative ratio of deuterium (%)	
		I	II	I	II
Quinoline	0	56	1	98	2
Quinoline	50	50	19	72	28
Quinoline	100	36	27	57	43
Quinoline	150	36	27	57	43
PPh_3	25	30	22	58	42

[a] A typical example of the procedure: to a solution of *cis*-β-methoxystyrene (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 ^{1}H NMR spectroscopy 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 ^{1}H NMR signals, using the methyl group as an internal standard. For the experiment performed using 100 mM 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. [b] Errors for the data are ±5%.

double bonds. The main side reactions in the reduction of alkynes to *cis*-alkenes are the further reduction and isomerisation of this product. It is well-documented that a triple bond is more vulnerable to nucleophillic attack than a double bond,[9] therefore, an increase in nucleophility of the metal hydrogen species should improve the selectivity for reduction of the triple bond. The shift from purely mode (*b*) (M$^{\delta-}$–H$^{\delta+}$) towards mode (*a*) (M$^{\delta+}$–H$^{\delta-}$), brought about by the modification of the catalyst with electron-rich ligands, clearly indicates that the metal hydrogen species is made more nucleophilic and hence provides a clue to the origin of the improved selectivity.

Interestingly, promotion of mode (*a*) (M$^{\delta+}$–H$^{\delta-}$) was previously found for the Lindlar catalyst (palladium modified with lead acetate) when it was compared to palladium on carbon.[8] The Lindlar catalyst also gives better selectivity for the reduction of alkynes to *cis*-alkenes, again suggesting that it is the change in the electronic properties of the palladium that is responsible for its improved reactivity.

This study establishes that quinoline and triphenylphosphine act as ligands for heterogeneous palladium and alter the electronic properties of the metal. This provides a new insight into how quinoline and triphenylphosphine may improve the selectivity of palladium catalysts for the semi-reduction of alkynes.

We thank the Royal Society for the award of a Royal Society University Research Fellowship (J.B.S.) and the British Council and the Chinese Government for the award of Sino-British Friendship Scholarship (J. Y.).

Notes and References

† E-mail: jbs20@cam.ac.uk

1 M. Friefelder, *Practical Catalytic Hydrogenation*, Wiley- Interscience, New York, 1971; P. Rylander, *Hydrogenation Methods*, Academic Press, New York, 1985.
2 K. Mori, *The Total Synthesis of Natural Products*, ed. J. ApSimon, Wiley-Interscience, New York, 1981, vol. 4; P. A. Bartlett, *Tetrahedron*, 1980, **36**, 3.
3 S. Siegel, in *Comprehensive Organic Synthesis*, ed. B. M. Trost and I. Fleming, Pergamon, 1991, vol. 8, pp. 418–440, and references cited therein.
4 A. B. McEwen, M. J. Guttieri, W. F. Maier, R. M. Laine and Y. Shvo, *J. Org. Chem*., 1983, **48**, 4436.
5 S. Siegel and J. A. Hawkins, *J. Org. Chem*., 1986, **51**, 1638.
6 J. A. Ulan, E. Kuo and W. F. Maier, *J. Org. Chem*., 1987, **52**, 3126.
7 J. Yu and J. B. Spencer, *J. Am. Chem. Soc.*, 1997, **119**, 5257.
8 J. Yu and J. B. Spencer, *J. Org. Chem.*, 1997, **62**, 8618.
9 R. W. Strozier, P. Caramella and K. N. Houk, *J. Am. Chem. Soc.*, 1979, **101**, 1340.

Received in Liverpool, UK, 22nd January 1998; 8/00629F