Observation of Burst Kinetics in Heterogeneous Catalytic Transfer Hydrogenolysis

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Arene formation by catalytic transfer hydrogenolysis of aryl tetrazolyl ethers in the liquid phase shows biphasic concentration–time curves indicating rate-limiting dissociation of heterogeneous complexes between catalyst and tetrazolone produced under steady state conditions.

Kinetic studies of heterogeneous, liquid phase catalytic hydrogen transfer reduction, in which a suitable hydrogen donor (other than molecular hydrogen) transfers its hydrogen to a substrate have been very limited. Early workers such as Wieland[1] pointed out the remarkable similarities of the donor–catalyst–acceptor model for catalytic transfer reduction to those of an enzyme system, *e.g.*, adsorption of both the donor and acceptor are necessary for reduction, together with competitive inhibition of the catalyst. This concept has been discussed in a review.[2] Here we present evidence that the kinetics of heterogeneous catalytic transfer hydrogenolysis in at least one reaction show remarkable similarities to the kinetics of certain enzyme-catalysed reactions exemplified by chymotrypsin.[3]

Hydrogenolysis of phenolic C–O bonds has been reported to proceed through heterogeneous catalytic transfer reduction of various phenolic ethers (ArOR) in which the group R [(**1**), reaction 1], needs to be strongly electron withdrawing and, for

$$\underset{(1)}{\mathrm{ArOR}} \xrightarrow[\text{catalyst}]{2\,\mathrm{H}} \underset{(2)}{\mathrm{ArH}} + \mathrm{HOR} \qquad (1)$$

convenience, is often 1-phenyltetrazolyl.[4] A large range of ethers (**1**) is available and the arenes (**2**) formed by hydrogenolysis are easily detected and measured by g.c. Kinetic studies on the hydrogenolysis of various aryl-substituted ethers (**1**; R = 1-phenyltetrazolyl) were undertaken to investigate electronic and steric effects on the rate of hydrogenolysis using commercial Pd/C as catalyst and sodium phosphinate as hydrogen donor in a two-phase water–ethanol–benzene system (see Table 1).

Owing to difficulties of reproducibility in the activity of commercial catalysts, for these heterogeneous systems competitive reductions of pairs of aryl ethers (**1**) with limited amounts of catalyst were investigated. For convenience, 5-(4-methoxyphenoxy)-1-phenyltetrazole (**1**; Ar = 4-methoxyphenyl) was used as standard.

Figure 1 shows typical arene concentration *vs.* time curves for the hydrogenolysis; it can be seen that, for each reaction profile, there is an initial burst in the formation of arene before a steady-state is achieved. For pairs of ethers, Table 1 gives relative steady-state reaction rates and ratios of extrapolated intercepts which represent relative initial adsorption of the aryl ethers onto the catalyst. For each ether, there is a similar ordering of relative steady-state reaction rates and extrapolated intercepts. The differences in steady-state rates of hydrogenolysis for a wide range of aryl-substituted ethers are not very great, suggesting that the substituents do not affect the rate determining step of the reaction electronically to a significant amount.

The graphs in Figure 1 are similar to concentration–time curves for certain enzyme-catalysed reactions;[3,5] the burst of arene is due to its rapid formation from ether initially adsorbed onto the catalyst. This first, rapid formation of arene is not maintained because the other product of reaction,

Table 1. Relative steady-state rates of cleavage and relative extrapolated intercepts for substituted aryl ethers (**1**; R = 1-phenyltetrazolyl) at 80 °C.

Ar (XC_6H_4), X =	*p*-CF_3	*o*-Me	*p*-CN	*m*-CN	*p*-NH_2	*p*-Me	*m*-Me	*p*-COMe	*p*-Bu^t	*p*-Ph	*m*-CF_3	*m*-NH_2	*p*-CO_2Ph	*p*-OMe
Relative steady state rate[a]	0.1	1.2	1.2	1.6	2.1	0.8	0.9	1.4	0.1	2.4	0.01	5.1	2.7	1.0
Relative extrapolated intercepts	0.3	1.5	4.2	5.4	10.2	0.9	1.7	10.4	0.2	5.3	0.1	9.7	6.1	0.00

[a] All reactions were carried out under the following typical conditions: the ether (150 mg) in ethanol (3 ml) and benzene (11 ml) was mixed with sodium phosphate (200 mg) in water (3.5 ml). To the mixture was added 10% Pd/charcoal catalyst (30 mg; Koch-Light; only one batch was used for all experiments) and the whole was refluxed. Samples of the reaction mixture were quenched by cooling to room temperature and analysed for arenes by g.c. on an OV 351 capillary column (25 m). Results of separate experiments show that these rate measurements are reproducible to about ± 6%.

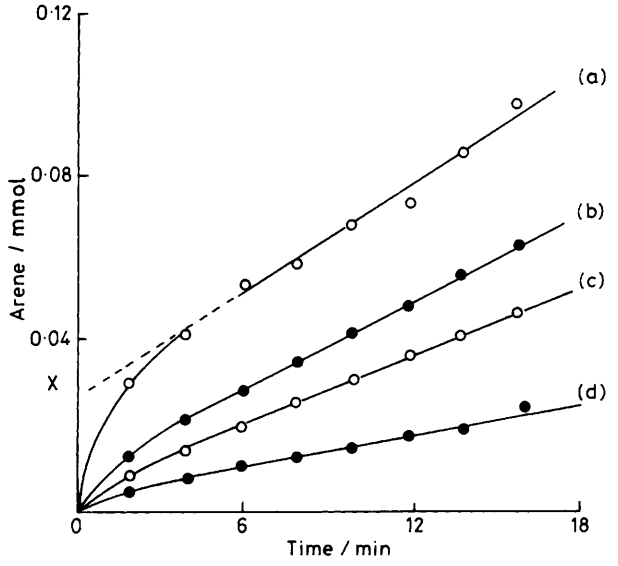

Figure 1. Plots showing the amount of arene formed with time for increasing amounts of substrate. Experiments were carried out at 80 °C under the conditions described in Table 1 using ethanol (3 ml), benzene (11 ml), water (3.0 ml), sodium phosphinate (150 mg), and 10% Pd/C catalyst (30 mg) with (a) 1.12, (b) 0.523, (c) 0.224, and (d) 0.075 mmol of 5-(4-methoxyphenoxy)-1-phenyltetrazole. Point X represents one of the extrapolated intercepts, its value being 3.5 times the standard deviation of the points on the graph.

1-phenyltetrazolone, does not desorb so readily from the catalyst. The subsequent steady-state formation of arene is largely governed by the rate of desorption of 1-phenyltetrazolone, and electronic changes resulting from variation in the substituents in the aryl ring of the ether (**1**) would not be expected to produce any marked variation in overall rate of hydrogenolysis. Addition of 1-phenyltetrazolone to the reaction mixture at the start of the reaction was found to cause a decrease in the initial burst phase of the reaction and in the steady-state rate, in keeping with the inferred inhibiting action for this product. Estimation (h.p.l.c.) of the adsorption of 1-phenyltetrazolone showed that it competed very effectively with the reactant ethers for sites on the catalyst surfaces. The reciprocal of the steady-state reaction rate for 5-(4-methoxyphenoxy)-1-phenyltetrazole correlates linearly with the reciprocal of the amount of substrate used, an observation analogous to Lineweaver–Burke plots for enzyme-catalysed reactions[4,5] in which substrate concentration is varied.

For enzymes, this whole pattern of kinetic behaviour is explained by extending the simple Michaelis–Menten[5–7] theory of enzyme kinetics to include, as well as an enzyme–substrate complex, an enzyme–product complex, the slow decomposition of which governs the overall rate of reaction. By analogy, the presence of a similar catalyst–product complex in reaction (1) would explain the observed small difference in reaction rates for a wide range of substituted aryl ethers. The rate determining step in the steady-state phase of the reaction would be the dissociation of an intermediate complex [(cat.)·HOR; reaction (2)] formed between the

$$\text{(cat.)} + \text{ArOR} \rightarrow \text{(cat.)}\cdot\text{ArOR} \xrightarrow{2H} \text{ArH} + \text{(cat.)}\cdot\text{HOR} \rightarrow \text{(cat.)} + \text{HOR} \quad (2)$$

catalyst and a product of hydrogenolysis (HOR), after decomposition of the initially formed complex [(cat.)·ArOR].

In summary, kinetic evidence for reaction (1) has revealed for the first time for heterogeneous catalytic transfer reduction in the liquid phase a mechanism which appears to be very similar to that of some homogeneous enzyme or complex-mediated reactions in that, after an initial burst of products, a steady-state rate is achieved and controlled by the rate of release of catalyst sites as one of the products desorbs slowly from the surface. The evidence also suggests strongly that the initial complexation of the aryl ethers to the catalyst surface is effected largely through the 1-phenyltetrazolyl part of the molecule. This conclusion would explain why other aryl ethers containing more powerfully electron-withdrawing groups (R) than 1-phenyltetrazolyl could not be hydrogenolysed.[3]

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