Effect of β-cyclodextrin on the bleaching of a triarylmethane dye by hydrogen peroxide and alkali

Pierre-Henri d'Hausen, Christopher N. Tait and D. Martin Davies *

Division of Chemistry, School of Applied and Molecular Sciences, University of Northumbria at Newcastle, Newcastle upon Tyne, UK NE1 8ST. E-mail: martin.davies@unn.ac.uk; Fax: 44 (0)191 2273519

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Bleaching of the triarylmethane dye, Green S, by hydrogen peroxide, involving nucleophilic attack at the electrophilic central carbon of the dye is first accelerated and then slowed down with increasing cyclodextrin concentration. This rate maximum is clear evidence for reaction pathways involving both one and two molecules of cyclodextrin. Because precise values of the 1 : 1 and 2 : 1 binding constants of the cyclodextrin and dye by an independent method could not be obtained, curve fitting is carried out using lower and upper limits of the product of the binding constants. This proves to be a useful approach in these circumstances. Alkali bleaching of the dye, also involving nucleophilic attack at the central carbon, is accelerated by cyclodextrin and the reverse reaction is slowed down, and no rate maxima or minima are observed. These results are consistent with pathways involving both one and two molecules of cyclodextrin provided the second cyclodextrin stabilises Green S and its alkali bleaching product to the same extent. The kinetic data are interpreted using the transition state pseudo-equilibrium constant approach, which has been extended to include reversible reactions. The results are discussed in terms of a simple cyclodextrin field effect.

Introduction

Our recent paper on the bleaching of the triarylmethane dye, Green S, is relevant to the oxidative remediation of polluted waters containing non-biodegradable materials.[1] We now extend previous studies[2–5] of the effects of cyclodextrins on the reactions of peroxides to include reactions with Green S. Cyclodextrins are effective in the remediation of soil matrices where they form complexes with organic pollutants and hence enhance their solubility.[6,7] It seems, therefore, that the solubilising ability of cyclodextrins coupled with their ability to catalyse peroxide reactions could be utilised in the oxidative remediation of soils. This paper explores the way in which complexation of Green S by one or two β-cyclodextrin molecules influences its reactivity.

Cyclodextrins are oligosaccharides produced enzymatically from starch. β-Cyclodextrin consists of seven α-(1,4) linked D-glucopyranose units forming a conical cylinder. As a consequence of the $^4C_1$ conformation of the glucopyranose units the seven primary hydroxy groups are situated at the narrower end of the cylinder and the 14 secondary hydroxy groups form the wider rim. Hydrogen bonding between the secondary hydroxy groups on adjacent glucopyranose units lends the molecule a more rigid structure than α-cyclodextrin where one of its six glucopyranose units is in a distorted position and the hydrogen bond belt is incomplete.[8] The stability of cyclodextrin complexes in solution has recently been reviewed, and their complexation thermodynamics, covalent catalysis, and field effects on organic reactions are described in a recent thematic issue of *Chemical Reviews*.[9,10]

Green S,[1] $\mathbf{HD}^-$ in Scheme 1, has a pK_a of 7.66. The conjugate base, $\mathbf{D}^{2-}$ has a pK_a of 11.72, which means that it starts to undergo alkali bleaching to form $\mathbf{D}(OH)^{3-}$ when the pH is raised above about 10. The pseudo-first-order rate constant for the approach to equilibrium during alkali bleaching, k_ψ, conforms to eqn. (1) where k_{H_2O} is the forward rate constant and the reverse rate constant, k_H, at a given pH is equivalent to $k_{-H_2O}[H^+]$. This is interpreted in terms of intramolecular base catalysis of the attack of H_2O on the central carbon by the neighbouring naphtholate O^-. The reverse reaction involves the attack of H^+ on $\mathbf{D}(OH)^{3-}$ as shown in Scheme 1. In the hydrogen peroxide bleaching of Green S the reaction of $\mathbf{D}^{2-}$ and H_2O_2 is also catalysed by the neighbouring O^-.

$$k_\psi = k_{H_2O} + k_H \equiv k_{H_2O} + k_{-H_2O}[H^+] \quad (1)$$

In the present study, the reaction of hydrogen peroxide and Green S exhibits a rate maximum with increasing β-cyclodextrin concentration. This is clear kinetic evidence for pathways involving both one and two molecules of cyclodextrin. Because of the limited solubility of the cyclodextrin, however, the results cannot be extended to a high enough concentration to characterise the second pathway precisely. Previously we have overcome this problem by utilising binding constants determined by an independent method in the treatment of the kinetic data.[2–4] Independent determination of the 1 : 1 and 2 : 1 binding constants of β-cyclodextrin and $\mathbf{D}^{2-}$ was not achieved in the present case because the changes in the UV–visible spectrum of the dye were small, particularly at higher cyclodextrin concentrations, and consistent with a wide range of 2 : 1 binding constants. (In this respect, Green S behaves like another triarylmethane dye, Phenolphthalein, for which, at lower pH, complex formation with β-cyclodextrin is evidenced by circular dichroism although there is little change in the UV–visible spectrum.[11]) It is necessary, therefore, to treat the kinetic data for the β-cyclodextrin-mediated reaction of hydrogen peroxide and Green S using the lower and upper limits of the product of the 1 : 1 and 2 : 1 binding constants of the cyclodextrin and dye. These limits are also applied to the cyclodextrin-mediated reversible alkali bleaching of the dye to yield consistent rate and binding constants.

Experimental

The determination of pseudo-first-order rate constants for the bleaching of Green S by hydrogen peroxide and by alkali has

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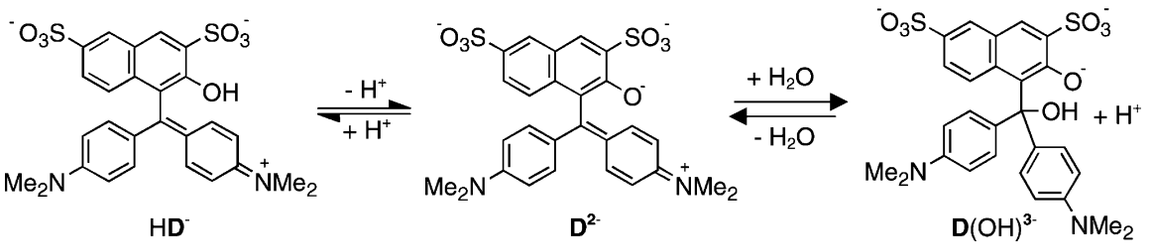
Table 1 Best-fit values (± standard deviation) of binding constants and rate constants for different $K_{11}^{D}K_{12}^{D}$

X	Y	$K_{11}^{D}K_{12}^{D}$/ $dm^6\ mol^{-2}$	K_{11}^{D}/ $dm^3\ mol^{-1}$	k_0^X/s^{-1}	k_{1obs}^X/ $dm^3\ mol^{-1}\ s^{-1}$	k_{2obs}^X/ $dm^6\ mol^{-2}\ s^{-1}$	K_{11}^{DOH}/ $dm^3\ mol^{-1}$	$K_{11}^{DOH}K_{12}^{DOH}$/ $dm^6\ mol^{-2}$
H_2O_2	$\mathbf{D}^{2-}$	14000	460 ± 120	0.0023 ± 0.0001	2.0 ± 0.4	0.5 ± 5		
H_2O_2	$\mathbf{D}^{2-}$	100000	230 ± 190	0.0022 ± 0.0001	1.4 ± 0.6	260 ± 100		
H_2O	$\mathbf{D}^{2-}$	14000	800 ± 170	0.00019 ± 0.00001	0.24 ± 0.04	4 ± 1		
H_2O	$\mathbf{D}^{2-}$	100000	830 ± 210	0.00019 ± 0.00001	0.24 ± 0.05	28 ± 1		
H^+	$\mathbf{D}(OH)^{3-}$	14000		0.0018 ± 0.0001			3500 ± 600	57000 ± 19000
H^+	$\mathbf{D}(OH)^{3-}$	100000		0.0018 ± 0.0001			3400 ± 700	400000 ± 40000



Scheme 1

been described previously.[1] In the present work, stock β-cyclodextrin (Fluka) solutions were prepared in buffer and diluted to the required concentration with buffer and the pH adjusted to the original value with NaOH as necessary. This is particularly important at the highest pH, 10.8, where the cyclodextrin, pK_a approximately 12.2, acts as a weak acid and the systematic decrease of pH with increasing cyclodextrin concentration would otherwise perturb the kinetics of alkali bleaching. Kinetic runs were carried out by mixing 1.8 ml of buffered cyclodextrin and 0.1 ml of hydrogen peroxide solution, or water in the case of alkali bleaching, in a cuvette and bringing to 25 °C in the thermostatic cell holder of a Pharmacia Biotech Ultrospec 2000 spectrophotometer. Reactions were initiated by mixing in 0.1 ml of Green S solution to give a final concentration 1.25×10^{-5} mol dm^{-3}. Bleaching of the dye was monitored at 615 nm.

Results

Fig. 1 shows typical changes in absorbance, A, during the alkali bleaching of Green S at pH 10.8 in the presence of varying amounts of cyclodextrin. Initial small changes in absorbance within the time of mixing represent the rapid equilibration between the dye and cyclodextrin and the cyclodextrin–dye complexes. The data conform to eqn. (2) for the duration of

$$A = A_\infty + \Delta A e^{-k_\psi t} \quad (2)$$

measurements, which is more than five half-lives. Best-fit values of k_ψ, A_∞ (the absorbance upon attainment of equilibrium) and ΔA (the difference between the initial absorbance and A_∞) were obtained by non-linear regression of eqn. (2). Eqns. (1) and (3)

$$\frac{\Delta A}{A_\infty} = \frac{k_{obs}^{H_2O}}{k_{obs}^{H}} \quad (3)$$

were then used to calculate the values of k_{H_2O} and k_H observed at each cyclodextrin concentration, $k_{obs}^{H_2O}$ and k_{obs}^{H}, shown in Fig. 2.

The bleaching of Green S by hydrogen peroxide at pH 9.8 went to completion and plots of $\ln(A - A_\infty)$ against time were linear for at least three half-lives. The pseudo-first-order rate constants, $k_{obs}^{H_2O_2}$ obtained by linear regression of the plots are plotted against cyclodextrin concentration in Fig. 3.

Data treatment

The dependence of k_{obs}^{X} values on cyclodextrin concentration is described by eqn. (4) where X is an identity variable for the Green S reaction partner, Y identifies the form of the dye, $\mathbf{D}^{2-}$ or $\mathbf{D}(OH)^{3-}$, k_0^X, k_{1obs}^X and k_{2obs}^X are the respective zero, first and second order dependences on cyclodextrin concentration and K_{11}^Y and K_{12}^Y are the respective 1 : 1 and 2 : 1 stepwise binding constants of the dye and cyclodextrin. Scheme 2 shows the thermodynamic cycles for the interaction of one and two molecules of cyclodextrin with the transition state formed by

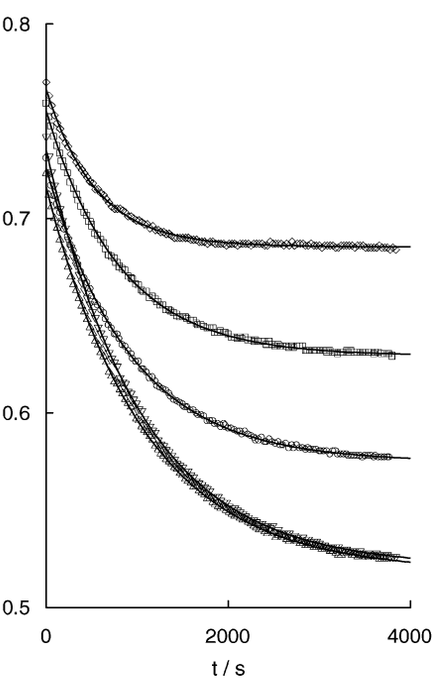
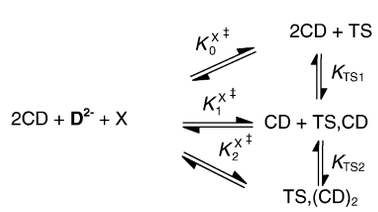


Fig. 1 Changes in absorbance at 615 nm during the alkali bleaching of 1.25×10^{-5} mol dm^{-3} Green S in carbonate buffer, pH 10.8, ionic strength 0.1 mol dm^{-3} at 25 °C at the following β-cyclodextrin concentrations/mol dm^{-3}: ◇ 0, □ 4.5×10^{-4}, ○ 9×10^{-4}, △ 2.7×10^{-3}, ▽ 8.1×10^{-3}. The curves show the best fit according to eqn. (2).



Scheme 2

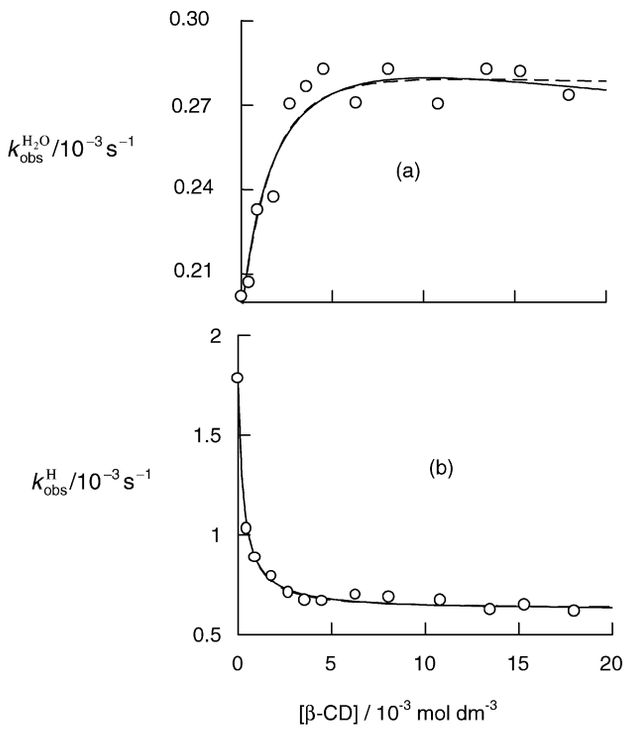


Fig. 2 Effect of cyclodextrin on (a) the forward and (b) the reverse rate constant of alkali bleaching; conditions as given in Fig. 1. The continuous and dashed curves represent the best-fit values of the parameters according to eqns. (4) and (9) corresponding to the respective lower limit and upper limit values of $K_{11}^{D}K_{12}^{D}$ in Table 1.

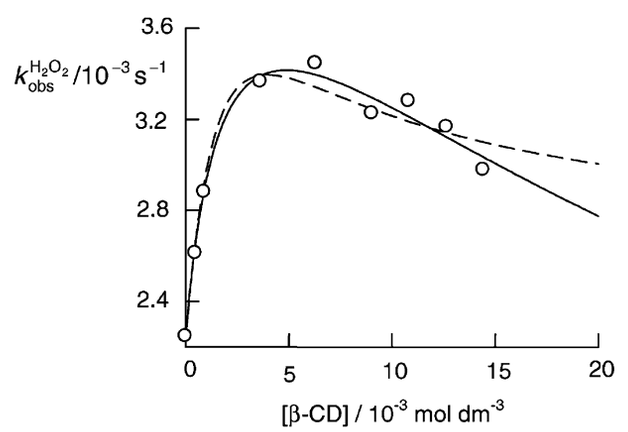
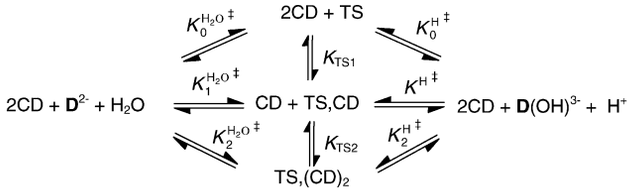


Fig. 3 Effect of cyclodextrin on the pseudo-first-order rate constants for reaction with 5.0×10^{-3} mol dm^{-3} H_2O_2 in carbonate buffer pH 9.8, ionic strength 0.1 mol dm^{-3}. The continuous and dashed curves represent the best-fit values of the parameters according to eqn. (4) corresponding to the respective lower limit and upper limit values of $K_{11}^{D}K_{12}^{D}$ in Table 1.

Green S and its reaction partner. Application of transition state theory to the cycles leads to eqns. (5) and (6) for the transition state pseudo-equilibrium constants K_{TS1} and K_{TS2}. K_{TS1} represents the stabilisation imparted to the transition state as a result of its association with one cyclodextrin molecule and K_{TS2} represents the additional stabilisation or the destabilisation imparted by a second cyclodextrin molecule. Eqn. (4) is fitted to the data for the bleaching of Green S by hydrogen peroxide and eqns. (5) and (6) are used to obtain the transition state pseudo-equilibrium constants. Scheme 3 shows the thermodynamic cycle for the reversible alkali hydrolysis of Green S that is an extension to the one used for the non-reversible reactions in Scheme 2. Application of transition state theory leads to the relation between the transition state equilibrium constants and the forward and reverse rate constants shown in eqns. (7) and (8). Taking eqn. (4) for the reverse reaction, *i.e.* with Y = $\mathbf{D}(OH)^{3-}$ and X = H^+, and substituting for k_{1obs}^{H} and k_{2obs}^{H} according to eqns. (7) and (8) leads to eqn. (9). The data for the reversible alkali bleaching of Green S shown in Fig. 2 are treated using eqn. (9) and eqn (4) with Y = $\mathbf{D}^{2-}$ and X = H_2O. Eqns. (7) and (8) are used to obtain the transition state pseudo-equilibrium constants.



Scheme 3

$$k_{obs}^{X} = \frac{k_0^X + k_{1obs}^X[CD] + k_{2obs}^X[CD]^2}{1 + K_{11}^Y[CD] + K_{11}^Y K_{12}^Y[CD]^2} \quad (4)$$

$$K_{TS1} = \frac{K_1^{X\ddagger}}{K_0^{X\ddagger}} = \frac{k_{1obs}^X}{k_0^X} \quad (5)$$

$$K_{TS2} = \frac{K_2^{X\ddagger}}{K_1^{X\ddagger}} = \frac{k_{2obs}^X}{k_{1obs}^X} \quad (6)$$

$$K_{TS1} = \frac{K_1^{H_2O\ddagger}}{K_0^{H_2O\ddagger}} = \frac{k_{1obs}^{H_2O}}{k_0^{H_2O}} = \frac{K_1^{H\ddagger}}{K_0^{H\ddagger}} = \frac{k_{1obs}^H}{k_0^H} \quad (7)$$

$$K_{TS2} = \frac{K_2^{H_2O\ddagger}}{K_1^{H_2O\ddagger}} = \frac{k_{2obs}^{H_2O}}{k_{1obs}^{H_2O}} = \frac{K_2^{H\ddagger}}{K_1^{H\ddagger}} = \frac{k_{2obs}^H}{k_{1obs}^H} \quad (8)$$

$$k_{obs}^{H} = \frac{k_0^H\left(1 + \frac{k_{1obs}^{H_2O}}{k_0^{H_2O}}[CD] + \frac{k_{2obs}^{H_2O}}{k_0^{H_2O}}[CD]^2\right)}{1 + K_{11}^{DOH}[CD] + K_{11}^{DOH}K_{12}^{DOH}[CD]^2} \quad (9)$$

Curve fitting

The hydrogen peroxide bleaching data shown in Fig. 3 exhibit a rate maximum rather than the simple saturation kinetics expected for systems where the oxidant does not bind to cyclodextrin and the dye forms only a 1 : 1 complex. These data indicate that a 2 : 1 cyclodextrin–dye complex is also present. However, attempts to fit the data using all of the parameters in eqn. (4) were unsuccessful. Examination of Fig. 3 makes it clear why this is so. The data points do not adequately define the form of the curve at high cyclodextrin concentration and are consistent both with a sharp decrease in $k_{obs}^{H_2O_2}$ to a fairly high limiting value (*i.e.* relatively large K_{12}^{D} and $k_{2obs}^{H_2O_2}$ compared to the 1 : 1 parameters) and with a much more gradual decrease to a much lower limiting value (*i.e.* relatively small K_{12}^{D} and $k_{2obs}^{H_2O_2}$). Moreover, the limited solubility of the cyclodextrin precludes extension of the data to higher concentrations. A solution to this problem is to substitute binding constants determined by an independent method into the equation and fit the data to the rate parameters only.[2–4] In the present case, though, attempts to obtain the binding constants of $\mathbf{D}^{2-}$ using UV–visible absorption spectroscopy were unsuccessful because changes in the dye spectrum were small, particularly at higher cyclodextrin concentrations, and consistent with a wide range of K_{12}^{D} values (results not shown). Hence we were constrained to exploring the limits of eqn. (4) at chosen constant values of $K_{11}^{D}K_{12}^{D}$. The first entry in Table 1 shows the best-fit values of the

parameters when $K_{11}^{D}K_{12}^{D}$ is set to 14000 $dm^6\ mol^{-2}$, represented by the continuous line in Fig. 3. Setting $K_{11}^{D}K_{12}^{D}$ less than 14000 $dm^6\ mol^{-2}$ gives indistinguishable fits to the data but leads to a negative value of $k_{2obs}^{H_2O_2}$, which represents a physical impossibility. Thus, this value of $K_{11}^{D}K_{12}^{D}$ represents its lower limit and the corresponding value of $k_{2obs}^{H_2O_2}$ its lower limit. The second entry in Table 1 shows the best-fit values obtained when $K_{11}^{D}K_{12}^{D}$ is set to 100000 $dm^6\ mol^{-2}$, and these are represented by the dashed line in Fig. 3, which begins to show a systematic deviation from the experimental data. Thus, this value of $K_{11}^{D}K_{12}^{D}$ represents a reasonable approximate upper limit, and the value of $k_{2obs}^{H_2O_2}$ represents its corresponding upper limit. It can be seen from the respective entries in Table 1 that the best-fit values of K_{11}^{D} and $k_{1obs}^{H_2O_2}$ show a slight dependence on the chosen value of $K_{11}^{D}K_{12}^{D}$ whereas the best-fit value of $k_{2obs}^{H_2O_2}$ is highly dependent on the chosen value.

The pooled data for the forward and reverse rate constants for the alkali bleaching of Green S were regressed using eqns. (4) and (9), substituting into eqn. (4) the respective values of the limits of $K_{11}^{D}K_{12}^{D}$ obtained with hydrogen peroxide. Table 1 gives the values of the respective best-fit parameters obtained that, in this case, include $K_{11}^{DOH}$and $K_{11}^{DOH}K_{12}^{DOH}$. Values of K_{11}^{D}, $k_{1obs}^{H_2O}$, and K_{11}^{DOH} are independent of the chosen value of $K_{11}^{D}K_{12}^{D}$, whereas $k_{2obs}^{H_2O}$ and $K_{11}^{DOH}K_{12}^{DOH}$ are highly dependent on the chosen value. Fig. 2 shows that the best-fit curves for the respective limits, represented by the continuous and dashed lines are virtually identical. The values of K_{11}^{D} obtained for the reversible alkali bleaching of the dye and for the peroxide reaction are in satisfactory agreement, taking into consideration the different buffer compositions used and the weak association of a component of the carbonate buffer with cyclodextrin.[4]

Discussion

It is known that the binding of hydrogen peroxide to α-cyclodextrin is very weak or undetectable.[12] The reasonable assumption has been made in the treatment of the present data [where there are no terms in peroxide binding constants in the denominator of eqn. (4)] that this is also the case for β-cyclodextrin. The rate maximum for the effect of cyclodextrin on the reaction of hydrogen peroxide and Green S shown in Fig. 3 is clear evidence for reaction pathways involving both one and two molecules of cyclodextrin and this is interpreted in terms of the existence of both 1 : 1 and 2 : 1 complexes of β-cyclodextrin and the dye. It follows that the alkali bleaching reaction of Green S should also be influenced by binding of both one and two molecules of cyclodextrin even though no maxima or minima are evident in the cyclodextrin dependence of the forward and reverse reactions shown in Fig. 2. This apparent inconsistency is explained below in terms of the second cyclodextrin stabilising the Green S and the product of the reversible alkali bleaching to the same extent. A complicating factor, due to the limited solubility of the cyclodextrin, is that measurements cannot be made at high enough concentrations to define the 2 : 1 binding constant precisely. Curve fitting is therefore carried out using lower limits and reasonable approximate upper limits of the product of the 1 : 1 and 2 : 1 binding constants of the cyclodextrin and Green S, $K_{11}^{D}K_{12}^{D}$, obtained from the reaction with hydrogen peroxide.

For comparative purposes, the kinetic and equilibrium parameters in Table 1 are best considered in terms of transition state pseudo-equilibrium constants. This approach was originally developed for acid–base catalysis by Kurz, and it has also been used to discuss enzyme catalysis and has been adapted by Tee for reactions mediated by cyclodextrins and other systems such as surfactant micelles.[13–15] In this paper the triangular thermodynamic cycles of Scheme 2 differ in form but not in principle[13] from the more usual rectangular cycles that would include the binding constants of the dye and cyclodextrin, K_{11}^{D} and K_{12}^{D}. Analogous triangular cycles have been used previously for the cyclodextrin-mediated reactions of peroxides with organic sulfides and *p*-nitrophenyl acetate.[3,4] The usefulness of the triangular cycles is that they lead directly to values of the transition state equilibrium constants, K_{TS1} and K_{TS2}, *via* the ratios of rate constants given in eqns. (5) and (6) and these can be compared with values of the binding constants K_{11}^{D} and K_{12}^{D}. Thus, the magnitude of K_{TS1} compared with K_{11}^{D} provides a quantitative comparison of the stabilisation of the transition state and the dye by a molecule of cyclodextrin that is independent of any prior assumptions about the mechanism of catalysis or inhibition. Extension of the thermodynamic cycles to include reversible reactions in Scheme 3 and the resulting eqns. (7) and (8) is self-evident.

Table 2 shows the binding constants and transition state pseudo-equilibrium constants derived from the data in Table 1, either directly or using eqns. (5), (6), (7) or (8), for comparison of the results of regression analyses using the limiting values of $K_{11}^{D}K_{12}^{D}$ of 14000 and 100000 $mol^2\ dm^{-6}$, respectively. For the reaction of hydrogen peroxide and $\mathbf{D}^{2-}$ the ratio of K_{TS1} to K_{11}^{Y} is calculated to be 1.9 or 2.7 respectively for the two limiting values of $K_{11}^{D}K_{12}^{D}$. This signifies catalysis by cyclodextrin. Values of K_{12}^{Y} and K_{TS2} in Table 2 are very dependent on the chosen limiting value of $K_{11}^{D}K_{12}^{D}$. Nevertheless, meaningful comparisons can be made. Involvement of a second cyclodextrin results in the inhibition of the reaction of hydrogen peroxide and the dye; the extent of this inhibition could be anything from essentially complete, with the ratio of K_{12}^{Y} and K_{TS2} equalling one hundred, to moderate, with the ratio being just over two. The pattern of catalysis followed by inhibition shown in Fig. 3 is also observed with the α-cyclodextrin-mediated cleavage of *p*-nitrophenyl acetate and with the α-cyclodextrin-mediated reactions of this ester and peroxide anions, and both rate maxima and minima have been described in a study of the cleavage of 4-carboxy-2-nitrophenyl alkanoates by α- and β-cyclodextrins.[4,16]

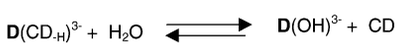
The alkali bleaching of $\mathbf{D}^{2-}$ shown in Fig. 2 is also catalysed, and the ratio of the corresponding values of K_{TS1} and K_{11}^{Y} in Table 2 show that the transition state is stabilised by a factor of about one and a half. The reverse of the alkali bleaching reaction is inhibited by cyclodextrin; the transition state is destabilised by a factor of about three. These factors are virtually independent of the limiting value of $K_{11}^{D}K_{12}^{D}$. Although the values of K_{12}^{Y} for $\mathbf{D}^{2-}$ and $\mathbf{D}(OH)^{3-}$ and the common transition state pseudo-equilibrium constant, K_{TS2}, for the reversible reaction are very dependent on the limiting value of $K_{11}^{D}K_{12}^{D}$, nevertheless the situation is very clear. The values of K_{12}^{Y} for $\mathbf{D}^{2-}$ and $\mathbf{D}(OH)^{3-}$ are virtually identical for a particular value of $K_{11}^{D}K_{12}^{D}$ showing that the second molecule of cyclodextrin stabilises the reactant and product of the reversible reaction to the same extent. It follows from transition state theory that the common transition state is also stabilised to the same extent. The second cyclodextrin molecule, therefore, performs no catalytic or inhibitory function. We have previously reported a similar situation where binding of a second cyclodextrin to 4-*tert*-butylperbenzoic, peroctanoic, and pernonanoic acids stabilises these peracids to the same extent as their transition states for reaction with aryl alkyl sulfides. We have suggested that this be termed 'neutral binding' as opposed to 'non-productive binding' where the cyclodextrin field inhibits the reaction.[3]

The present study includes the effect of cyclodextrin on the kinetics of the approach to equilibrium during alkali bleaching at pH 10.8. Previous equilibrium studies of the interaction of β-cyclodextrin and another triarylmethane dye, Phenolphthalein, at pH 10.5 have also been interpreted in terms of the formation of a colourless inclusion complex between the cyclodextrin and the dye. One author suggests the involvement of a postulated lactonoid dianion form of the dye, rather than the carbinol form or a covalent complex in which the central carbon of the dye is bound to a hydroxy oxygen of the cyclodextrin.[17] The

Table 2 Binding constants and transition state pseudo-equilibrium constants (± standard deviation) for different $K_{11}^{D}K_{12}^{D}$

X	Y	$K_{11}^{D}K_{12}^{D}$/dm^6 mol^{-2}	K_{11}^{Y}/dm^3 mol^{-1}	K_{TS1}/dm^3 mol^{-1}	K_{12}^{Y}/dm^3 mol^{-1}	K_{TS2}/dm^3 mol^{-1}
H_2O_2	$\mathbf{D}^{2-}$	14000	460 ± 120	890 ± 180	30 ± 8	0.3 ± 3
H_2O_2	$\mathbf{D}^{2-}$	100000	230 ± 190	630 ± 270	430 ± 360	190 ± 80
H_2O	$\mathbf{D}^{2-}$	14000	800 ± 170	1260 ± 210	18 ± 4	17 ± 4
H_2O	$\mathbf{D}^{2-}$	100000	830 ± 210	1250 ± 260	120 ± 30	120 ± 30
H^+	$\mathbf{D}(OH)^{3-}$	14000	3500 ± 600	1200 ± 210	16 ± 5	17 ± 4
H^+	$\mathbf{D}(OH)^{3-}$	100000	3400 ± 700	1250 ± 260	120 ± 30	120 ± 30

involvement of a lactone dianion has been disputed and it has been stated that "the spectrum of the complex most resembles that of the colourless base [carbinol] formed in alkali medium" although these authors also believe that the carboxylate substituent plays a central role and interacts with the central carbon, possibly through a water molecule.[11] In the present work at pH 10.8 the formation of the colourless complex between β-cyclodextrin and Green S cannot possibly involve a carboxylate substituent forming a lactone ring at the central carbon because the dye simply does not have a carboxylate. Therefore, either carbinol formation is involved, as shown for the overall reaction in Scheme 3, or the central carbon of the dye is covalently bound to the conjugate base of cyclodextrin, releasing H^+ and forming $\mathbf{D}(CD_{-H})^{3-}$. This is analogous to the well-known acyl transfer from esters to cyclodextrin, such as that involving 2-nitrophenyl acetate and β-cyclodextrin.[18] In some cases two cyclodextrins cooperate in such an ester cleavage.[16,19] Thus, it is possible that a second cyclodextrin is involved in $\mathbf{D}(CD_{-H})^{3-}$ formation. It is perfectly correct to use a thermodynamic cycle of the form shown in Scheme 2 to compare irreversible processes that include both covalent interactions, such as acyl transfer from ester to cyclodextrin, and field effects, such as acyl transfer from the ester to an attacking nucleophile.[4] It is, however, worth clarifying the situation for reversible reactions. If alkali bleaching in the presence of cyclodextrin were to involve covalent bonding of the dye to cyclodextrin then obviously the reverse reaction would involve breaking of this bond. Hence the thermodynamic cycles on the right hand side of Scheme 3 concerning the reverse reaction should be modified to include the equilibrium shown in



Scheme 4

Scheme 4, relating the initial products of the forward reaction formed in the presence and absence of cyclodextrin. If $\mathbf{D}(CD_{-H})^{3-}$ is simply an intermediate then this has no effect on Scheme 3 and the general kinetic equation, eqn. (4), still holds for the reverse reaction. If a significant amount of $\mathbf{D}(CD_{-H})^{3-}$ is present once equilibrium is achieved, then the process shown in Scheme 4 should be included explicitly in the thermodynamic cycles, although it will not change the dependence on cyclodextrin concentration from that of eqn. (4) but simply involve additional terms in the denominator of eqn. (4) that include the equilibrium constant for the process. If the equilibrium shown in Scheme 4 is slow compared with the approach to equilibrium *via* the cyclodextrin-free and cyclodextrin-mediated pathways then the thermodynamic cycle still holds because the products of each individual reversible pathway are in equilibrium *via* the reactants. This argument will not be pursued further in the present paper because we have not attempted to differentiate experimentally between $\mathbf{D}(OH)^{3-}$ and $\mathbf{D}(CD_{-H})^{3-}$.

Field effects

Connors *et al.*, basing their reasoning on the opposing effects of *para* substituents on the binding constants of substituted benzoic acids and benzoate anions with α-cyclodextrin, suggested that benzoic acids bind in the cyclodextrin cavity with the carboxylic acid moiety at the narrow end of the cavity, whereas the carboxylate moiety is positioned at the wider secondary hydroxy end.[20] In contrast to this, *para* substituents have similar effects on the binding constants of perbenzoic acids and perbenzoate anions that mirror their effect on benzoic acid binding. This suggests that not only is the COOOH moiety located at the narrow end of the cavity but also the $COOO^-$.[12] The difference between the carboxylate and the percarboxylate is that space-filling molecular models show that the outer peroxygen atom holding a localised negative charge resides outside the cyclodextrin cavity. This is not possible for the charged COO^- moiety because the end of the rather narrow α-cyclodextrin cavity acts as a bottle neck to the benzene ring,[21] preventing it moving far enough to protrude from the narrow end of the cavity. Binding of substituted perbenzoic acids to α-cyclodextrin with the OOH at the narrow end of the cavity enhances their electrophilicity with respect to reaction with organic sulfides or iodide.[3] This is consistent with a field effect in which the narrow end of the cyclodextrin, which constitutes the positively charged end of the cyclodextrin dipole attracts the iodide or sulfide nucleophile to the outer peroxidic oxygen at the narrow end of the cavity.[3] In a similar way, binding of peracids including perbenzoic acids, decreases the apparent pK_a of the peracid due to the repulsion of the proton.[2,12] In contrast, binding of a perbenzoate anion with the OO^- at the narrow end of the cyclodextrin cavity lowers its nucleophilicity toward attack on the carbonyl carbon of *p*-nitrophenyl acetate.[4] This is consistent with the same field effect of cyclodextrin as before, but in this case it tends to repel the electrophilic carbonyl carbon. The effect of the cyclodextrin field on the reactivity of groups at the wider end of the cyclodextrin cavity, however, is not consistent with a field effect represented by a single dipole over the whole of the molecule. Thus, electrophilic attack by peroxides on cyclodextrin-bound aryl alkyl sulfides at the wider end of the cyclodextrin cavity is inhibited and, consistent with this, nucleophilic attack by peroxide anions on *p*-nitrophenyl acetate is generally moderately accelerated.[3,4] The present work focuses on the effect of cyclodextrin binding on the reactivity of Green S at the central carbon that is subject to intramolecular base catalysis.

The simplest explanation of the results is as follows. In the 1 : 1 cyclodextrin complex the $(CH_3)_2NC_6H_4$ moiety is included in the cyclodextrin cavity leaving the central carbon of the dye and the neighbouring O^- in a position where the field effect attracts the nucleophilic oxygen atoms of hydrogen peroxide or water and accelerates the reactions, the same field effect repels the proton released during the course of these reactions. Similarly it inhibits the attack of the proton during the reverse reaction in alkali bleaching. In the 2 : 1 complex at least one cyclodextrin binds to a $(CH_3)_2NC_6H_4$ moiety of Green S so that the narrow end of its cavity is adjacent to the central carbon of the dye, otherwise the dye would be too far inside one cyclodextrin cavity to be able to bind to the other. The other cyclodextrin is unlikely to bind to the naphthyl group since space-filling molecular models show that one of the charged sulfonate groups would be located deep inside the cyclodextrin cavity, which would involve an unfavourable desolvation energy. Most

probably the other cyclodextrin also binds to a $(CH_3)_2NC_6H_4$ moiety so as to sterically hinder the approach of hydrogen peroxide to the central carbon and neighbouring catalytic O^-. This causes the observed rate deceleration of the hydrogen peroxide reaction at higher cyclodextrin concentrations. The lack of effect of the second cyclodextrin on the alkali bleaching reaction and its reverse means that this cyclodextrin, unlike the first, stabilises each form of the dye, equally. This is different from the effect of the second cyclodextrin on the hydrogen peroxide reaction and may be a consequence of the cyclodextrin-mediated alkali bleaching actually involving formation of $\mathbf{D}(CD_{-H})^{3-}$, in which case the transition states of the two reactions would experience different field effects due to the second cyclodextrin. As described above, this would not invalidate the transition state pseudo-equilibrium constant approach utilised here. Further discussion, however, is unwarranted in the absence of experimental characterisation of the cyclodextrin-mediated alkali-bleached form of the dye and the myriad of specific effects that might alter the field experienced by H_2O_2 and H_2O if the latter was indeed involved in the cyclodextrin-mediated alkali bleaching.

Finally, it is worth noting that the orientation of β-cyclodextrin so that the narrow end of its cavity is adjacent to the central carbon of Green S, with the electron-donating dimethylamine substituent at the wider end of the cavity, is that expected from the field effect of the overall dipole of the cyclodextrin molecule.[22] This orientation is feasible from consideration of space-filling models (Fig. 4), and the cyclodextrin dipole would provide the field required for the observed rate acceleration for the reactions of the 1 : 1 cyclodextrin–$\mathbf{D}^{2-}$ complex.

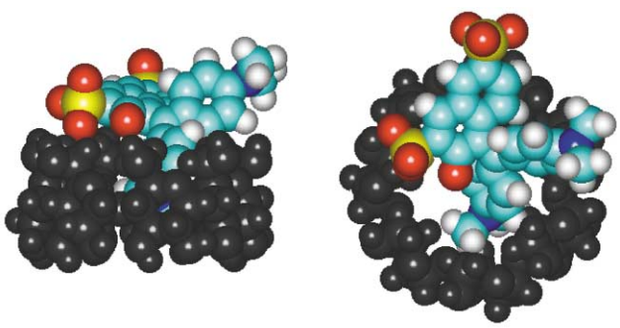


Fig. 4 Side (a) and top (b) views of a space filling model of a β-cyclodextrin–Green S complex showing the exposed reactive central carbon and neighbouring catalytic naphtholate O^- atom of the dye in its lowest energy, propeller-shaped, conformation.

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References

1 D. M. Davies and A. U. Moozyckine, *J. Chem. Soc., Perkin Trans. 2*, 2000, 1495.
2 D. M. Davies, G. A. Garner and J. R. Savage, *J. Chem. Soc., Perkin Trans. 2*, 1994, 1531; D. M. Davies and M. E. Deary, *J. Phys. Org. Chem.*, 1996, **9**, 433.
3 D. M. Davies and M. E. Deary, *J. Chem. Soc., Perkin Trans. 2*, 1996, 2423.
4 D. M. Davies and M. E. Deary, *J. Chem. Soc., Perkin Trans. 2*, 1999, 1027.
5 M. E. Deary and D. M. Davies, *Carbohydr. Res.*, 1998, **309**, 17; M. E. Deary and D. M. Davies, *Carbohydr. Res.*, 1999, **317**, 10.
6 A. R. Hedges, *Chem. Rev.*, 1998, **98**, 2035.
7 P. Sawunyama, M. Jackson and G. W. Bailey, *J. Colloid Interface Sci.*, 2001, **237**, 153; M. L. Brusseau, X. Wang and Q. Hu, *Environ. Sci. Technol.*, 1994, **28**, 952; M. L. Brusseau, X. Wang and W.-Z. Wang, *Environ. Sci. Technol.*, 1997, **31**, 1087.
8 J. Szejtli, *Chem. Rev.*, 1998, **98**, 1743.
9 K. A. Connors, *Chem. Rev.*, 1997, **97**, 1325.
10 M. V. Rekharsky and Y. Inoue, *Chem. Rev.*, 1998, **98**, 1875; R. Breslow and S. D. Dong, *Chem. Rev.*, 1998, **98**, 1997; K. Takahashi, *Chem. Rev.*, 1998, **98**, 2013.
11 A. Buvari, L. Barcza and M. Kajtar, *J. Chem. Soc., Perkin Trans. 2*, 1988, 1687.
12 D. M. Davies and M. E. Deary, *J. Chem. Soc., Perkin Trans. 2*, 1996, 2415.
13 J. L. Kurz, *J. Am. Chem. Soc.*, 1963, **85**, 987; J. L. Kurz, *Acc. Chem. Res.*, 1972, **5**, 1.
14 J. Kraut, *Science*, 1988, **242**, 533; A. J. Kirby, *Angew. Chem., Int. Ed. Engl.*, 1996, **35**, 707; S. J. Eustace, G. M. McCann, R. A. More O'Ferrall, M. G. Murphy, B. A. Murray and S. M. Walsh, *J. Phys. Org. Chem.*, 1998, **11**, 519.
15 O. S. Tee, *Carbohydr. Res.*, 1989, **192**, 181; O. S. Tee, *Adv. Phys. Org. Chem.*, 1994, **29**, 1; O. S. Tee and O. J. Yazbeck, *Can. J. Chem.*, 2000, **78**, 1100.
16 O. S. Tee and X.-x. Du, *J. Am. Chem. Soc.*, 1992, **114**, 620.
17 K. Taguchi, *J. Am. Chem. Soc.*, 1986, **108**, 2705; K. Taguchi, *J. Chem. Soc., Perkin Trans. 2*, 1992, 17.
18 R. L. Van Etten, J. F. Sebastian, G. A. Clowes and M. L. Bender, *J. Am. Chem. Soc.*, 1967, **89**, 3242; R. L. Van Etten, J. F. Sebastian, G. A. Clowes and M. L. Bender, *J. Am. Chem. Soc.*, 1967, **89**, 3253.
19 J. B. Giorgi and O. S. Tee, *J. Am. Chem. Soc.*, 1995, **117**, 3633.
20 K. A. Connors, S.-F. Lin and A. B. Wong, *J. Pharm. Sci.*, 1982, **71**, 217.
21 Y. Inoue, *Annu. Rep. N. M. R. Spectrosc.*, 1993, **27**, 59.
22 M. Sakurai, M. Kitagawa, H. Hoshi, Y Inoue and R. Chujo, *Carbohydr. Res.*, 1990, **198**, 181; D. M. Davies and M. E. Deary, *J. Chem. Soc., Perkin Trans. 2*, 1995, 1287; D. M. Davies and J. R. Savage, *J. Chem. Res. (S)*, 1993, 94; D. M. Davies and J. R. Savage, *J. Chem. Res. (M)*, 1993, 660.