

A STUDY OF THE KINETICS OF INCLUSION OF HALONAPHTHALENES WITH β -CYCLODEXTRIN VIA TIME CORRELATED PHOSPHORESCENCE

NICHOLAS J. TURRO*, JOHN D. BOLT, YASUHISA KURODA† and IWAQ TABUSHI†

Chemistry Department, Columbia University, New York, NY 10027, USA and
†Department of Synthetic Chemistry, Kyoto University, Yoshida, Kyoto 606, Japan

(Received 13 July 1981; accepted 18 August 1981)

Abstract The phosphorescence of 1-bromonaphthalene and 1-chloronaphthalene is readily observable in nitrogen purged aqueous solutions containing β -cyclodextrin. Addition of acetonitrile increases both the phosphorescence intensity and lifetime. The quenching of halonaphthalene phosphorescence in aqueous solution by nitrite is substantially inhibited upon addition of β -cyclodextrin, as a result of a guest host complex. The rate constants for formation and dissociation of the 1-bromonaphthalene- β -cyclodextrin complex are evaluated from an analysis of the dependence of phosphorescence lifetimes on nitrite concentration.

INTRODUCTION

Cyclodextrins are water soluble cyclic oligosaccharides that are shaped like doughnuts, and which contain hydrophobic cavities. (Saenger, 1980; Bender and Komiyama, 1978). Many organic and inorganic molecules form inclusion complexes with cyclodextrins in which the (guest) molecule becomes included in the cyclodextrin (host) pocket. Typically, one-to-one guest host complexes are formed (Saenger, 1980; Bender and Komiyama, 1978; Cramer *et al.*, 1967), although several examples are known of complexes containing two guests to one host (Ueno *et al.*, 1980; Ueno *et al.*, 1981; Rideout and Breslow, 1980; Tabushi *et al.*, 1979).

The kinetics of one-to-one host/guest association have been studied by T-jump (Cramer *et al.*, 1980) and ultrasonic relaxation (Rohrbach *et al.*, 1977). With recent measurement of the exchange dynamics of phosphorescent arenes between micelles and the aqueous phase in mind (Almgren *et al.*, 1979; Turro and Aikawa, 1980; Bolt and Turro, submitted), we sought to measure cyclodextrin-guest exchange kinetics by analogous methods. The basic scheme involves selective quenching of phosphorescence in the aqueous phase when the triplet arene is dissociated. In appropriate limiting cases, the phosphorescence lifetime of the guest will be determined by the escape rate from the cyclodextrin cavity. This method assumes that the dynamics of a triplet arene are essentially the same as those of a ground state arene.

*To whom correspondence should be sent.

†Abbreviations: β -CD, β -cyclodextrin; τ_p , phosphorescence lifetime; Q, quencher; *N, triplet state halonaphthalene.

MATERIALS AND METHODS

1-Bromonaphthalene and 1-chloronaphthalene (Aldrich) were vacuum distilled. Sodium nitrite was recrystallized twice from water. Water was twice distilled. Acetonitrile (Aldrich spectrograde) and β -cyclodextrin (Aldrich) were used as supplied.

Luminescence spectra were recorded on a Perkin-Elmer Hitachi MPF-3L spectrofluorimeter. Phosphorescence lifetimes were measured as described previously (Turro and Aikawa, 1980). Sample solutions were passed through millipore filters and then bubbled with nitrogen (Linde oxygen-free grade) for approx. 20 min at 0°C.

RESULTS AND DISCUSSION

The lifetime and intensity of 1-bromonaphthalene phosphorescence in aqueous β -cyclodextrin (β -CD)† solution were found to be sensitive to the concentration of acetonitrile (Fig. 1). As the percentage of CH_3CN increased the phosphorescence intensity increased and the phosphorescence lifetime approached a value of 1.7 ms. In the absence of β -CD a slight decrease in lifetime was observed upon addition of CH_3CN . Similar behavior was observed for 1-chloronaphthalene. However, for 2-bromonaphthalene no effect of CH_3CN was observed (Fig. 1). These results suggest formation of a complex composed of β -CD, 1-halonaphthalene and one (or possibly more) CH_3CN molecules. Previous work (Harata and Uedaira, 1975) has shown that large differences, due to steric effects, exist in the ability of 1- and 2-substituted naphthalenes.

In light of these results, the quenching of 1-bromonaphthalene by NaNO_2 was studied in β -CD solutions containing 10% CH_3CN , Figs. 2 and 3. At 28°C, τ_p approaches a plateau level of 140 μs at 0.1–0.3 mM NaNO_2 . In the absence of β -CD, two orders of magnitude less NO_2^- is required to quench

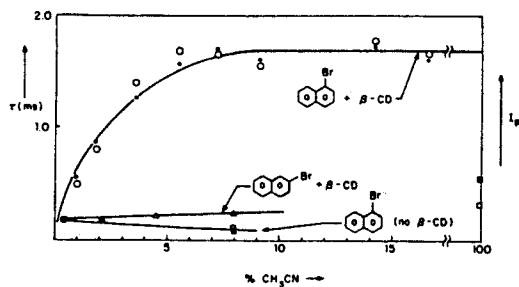


Figure 1. The effect of acetonitrile on the lifetime, τ_p , and intensity of phosphorescence from 1- and 2-bromonaphthalenes in the presence of β -CD, in aqueous solution. Solid symbols = lifetimes, ms. Open symbols = intensity, arbitrary scale.

1-bromonaphthalene phosphorescence to a comparable extent. In analogy to the micellar systems studied by Almgren *et al.* (1979), the behavior shown in Figs. 2 and 3 indicates that escape from the β -CD cavity is becoming the rate limiting step for the quenching of 1-bromonaphthalene phosphorescence. The protective effect of β -CD supports the proposed complex formation. The naphthohydroquinone anion radical was reported to be protected by the β -CD cavity (Tabushi *et al.*, 1979).

At 5°C, much greater concentrations of NO_2^- are required to quench the phosphorescence, Fig. 3. Plateau values are not completely obtained at even the highest quencher concentrations, indicating significant quenching of 1-bromonaphthalene within the β -CD complex. At intermediate NO_2^- concentrations quenching is dependent on the β -CD concentration, indicative of competition between quenching of free 1-bromonaphthalene and reentry into the β -CD complex. These observations are embodied in Scheme 1, which defines the pathways for decay of the triplet state halonaphthalene. *N. In scheme 1,

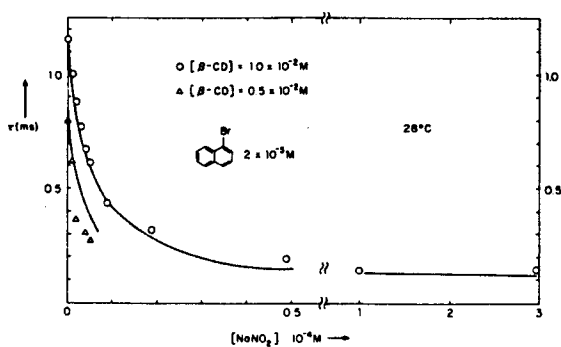
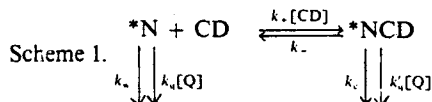


Figure 2. Quenching of 1-bromonaphthalene phosphorescence lifetime by NaNO_2 in the presence of β -CD. Experimental points at 28°C. The solid line is calculated according to Eq. 1 from parameters given in Table 1.

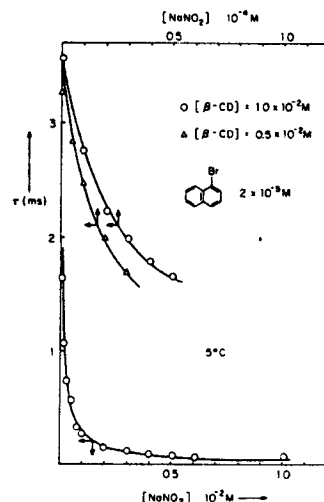


Figure 3. Same as Fig. 2, but at 5°C. Note the expanded scale for the upper curves.

CD represents β -cyclodextrin (containing CH_3CN); k_w and k_c are the unimolecular decay rates of the triplet probe in the aqueous phase and within the β -CD complex; k_q and k'_q are the bimolecular quenching rate constants of triplet probe in free solution and in the complex, respectively. k_+ and k_- are the second order formation and first order dissociation rate constants of the complex, respectively. Based on Scheme 1, the observed decay rate k_0 ($= 1/\tau_0$) is given by Eq. 1 (Almgren *et al.*, 1979; Turro and Aikawa, 1980):

$$\begin{aligned} \frac{1}{\tau_0} &= k_0 \\ &= k_c + k_- - \frac{k_+ k_- [\text{CD}]}{k_+ [\text{CD}] + k_w + k_q [\text{Q}]} + k'_q [\text{Q}] \end{aligned} \quad (1)$$

k_w and k_q can be determined independently in aqueous solution; k_c is the reciprocal of τ_p in the presence of β -CD and in the absence of quencher. Due to the $k'_q [\text{Q}]$ term, k_+ and k_- could not be determined analytically. Almgren *et al.* (1979) and Turro and Aikawa (1980) were able to ignore k'_q due to charge repulsion of quencher and micelle. The data of Figs. 2 and 3 were fitted to Eq. 1 using a computer program. The results and range of values determined by the fit are given in Table 1.

From Table 1, the formation, k_+ , and dissociation, k_- , rate constants are comparable to those of other guest-host cyclodextrin complexes (Saenger, 1980; Cramer *et al.*, 1967). However, the dissociation equilibrium constant,

$$K_D \left(= \frac{k_-}{k_+} \right)$$

is an order of magnitude smaller than the previous values. For the complex of 1-bromonaphthalene and β -CD, $K_D \approx 10^{-4} M$ at 15°C. 1-Bromonaphthalene is

Table 1. Kinetic parameters for the association of 1-bromonaphthalene with β -cyclodextrin and for quenching by sodium nitrite*

T (°C)	k_+ ($s^{-1} M^{-1}$)	k_- (s^{-1})†	k_w (s^{-1})†	k_c (s^{-1})†	k_q ($s^{-1} M^{-1}$)†	k'_q ($s^{-1} M^{-1}$)‡
5	$(5 \pm 1) \times 10^7$	$(8 \pm 2) \times 10^2$	2×10^3	280	3.1×10^9	2.6×10^6
15	$(7 \pm 4) \times 10^7$	$(6 \pm 3) \times 10^3$	3.2×10^3	400	3.4×10^9	3.2×10^6
28	$(10 \pm 5) \times 10^7$	$(4 \pm 3) \times 10^4$	6.5×10^3	700	3.8×10^9	4.0×10^6

* In H_2O containing 10% CH_3CN according to Scheme 1.† $\pm 15\%$.‡ $\pm 40\%$.Table 2. 1-Halonaphthalene complexes with β -cyclodextrin. effect of acetonitrile*

Halonaphthalene	CH_3CN	k_+ ($M^{-1} s^{-1}$)	k_- (s^{-1})	K_D (M)
1-Bromo	10%	8×10^7	1×10^4	10^{-4}
1-Bromo	2%	2×10^7	2×10^4	10^{-3}
1-Chloro	2%	1×10^7	1×10^4	10^{-3}

* Error limits as in Table 1; 20°C.

much less polar than previous substrates which have typically been organic anions (Bender and Komiyama, 1978).

The temperature dependence of k_- is remarkably large, Table 1, corresponding to an apparent activation energy of 109 ± 38 kJ/mol. From the temperature dependence of K_D we calculate $\Delta H = 96$ kJ/mol and $\Delta S = 60$ e.u. for the overall dissociation equilibrium.

The effect of CH_3CN on the binding of 1-bromo- and 1-chloronaphthalene is shown in Table 2. The eightfold greater binding at high acetonitrile concentration can be attributed primarily to acceleration of k_+ .

The protective effect of β -CD against quenching is emphasized by the readily observed phosphorescence

of 1-chloronaphthalene (Fig. 4). Observation of the phosphorescence of 1-chloronaphthalene in homogeneous solution and in micelles requires time-resolved techniques (Turro and Aikawa, 1980). In no case have we been able to observe this emission using steady state excitation. It appears that the β -CD complex protects 1-halonaphthalenes from trace impurity quenchers, including residual molecular oxygen and from self-quenching.

In contrast to the results with 1-bromonaphthalene, nitrite quenching of 2-bromonaphthalene in β -CD solution showed neither an appreciable CH_3CN effect nor an appreciable temperature dependence. However, the phosphorescence quenching by nitrite was suppressed fivefold over that in the absence of β -CD. We propose that k'_q is the dominant term for quenching of 2-bromonaphthalene.

In conclusion, 1-halonaphthalenes form inclusion complexes with β -CD. Complex formation enhances triplet lifetime and the intensity of phosphorescence. The kinetics of complex formation and dissociation can be investigated by analysis of phosphorescence quenching by aqueous quenchers. The results contribute to the use of room temperature phosphorescence as a probe of molecular dynamics in the microsecond to millisecond time domain.

Acknowledgements—The authors thank the National Science Foundation for their generous support of this research. Y.K. and I.T. thank the Institute for Molecular Science (Japan) for a Special Cooperative Research Project Grant for its support of this work.

REFERENCES

- Almgren, M., F. Grieser and J. K. Thomas (1979) *J. Am. Chem. Soc.* **101**, 279-291.

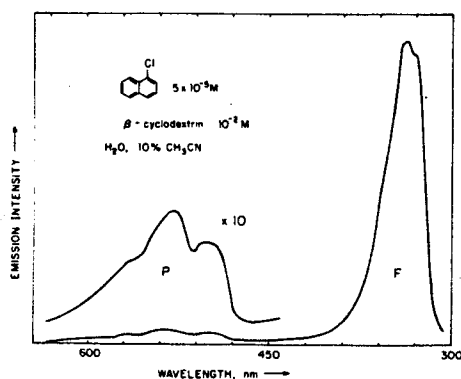


Figure 4. Steady state emission of 1-chloronaphthalene in β -CD solution. Fluorescence (F) and phosphorescence (P) are readily observed at 25°C. Excitation at 295 nm; band-pass is 5 nm for excitation and emission. Uncorrected for detection response.

- Bender, M. L. and M. Komiyama (1978) *Cyclodextrin Chemistry*. Springer-Verlag, Berlin.
- Cramer, F., W. Saenger and H-Ch. Spatz (1967) *J. Am. Chem. Soc.* **89**, 14-20.
- Harata, K. and H. Uedaira (1979) *Bull. Chem. Soc. Jpn.* **48**, 375-378.
- Rideout, D. C. and R. Breslow (1980) *J. Am. Chem. Soc.* **102**, 7816-7817.
- Rohrbach, R. P., L. J. Rodriguez, E. M. Eyring and J. F. Wojcik (1977) *J. Phys. Chem.* **81**, 944-948.
- Saenger, W. (1980) *Angew. Chem. (Int. Ed.)* **19**, 344-362.
- Tabushi, I., K. Fujita and L. C. Yuan (1977) *Tetrahedron Lett.* 2503-2506.
- Tabushi, I., C. Yamamura, K. Fujita and H. Kawakubo (1975) *J. Am. Chem. Soc.* **101**, 1019-1026.
- Turro, N. J. and M. Aikawa (1980) *J. Am. Chem. Soc.* **102**, 4866-4870.
- Ueno, A., K. Takahashi and T. Osa (1980) *J. Chem. Soc. Chem. Commun.* 921-922.
- Ueno, A., K. Takahashi, Y. Hino and T. Osa (1981) *J. Chem. Soc. Chem. Commun.* 194-195.