A Fluorescent α-Cyclodextrin as a Sensor for Detecting Aliphatic Alcohols by Dual Fluorescence arising from Normal Planar and Twisted Intramolecular Charge Transfer Excited States

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A *p*-dimethylaminobenzoyl moiety attached to α-cyclodextrin exhibits dual emissions from normal planar and twisted intramolecular charge transfer excited states and may be used as a fluorescent sensor for detecting aliphatic compounds such as n-pentanol and n-hexanol.

Cyclodextrins (CyDs) are cyclic oligosaccharides composed of six or more D-glucopyranose units. The six, seven and eight D-glucopyranose members of CyDs are named as α, β- and γ-CyD, respectively, and form inclusion complexes with various organic compounds in aqueous solution.[1,2] The guest binding of CyD is related to the cavity size and changed by specific modification. With a view of detecting various organic compounds by using this inclusion phenomenon, it is necessary to modify CyDs to make them exhibit any spectroscopic response. Recently, Ueno *et al.* prepared a variety of chromophore-attached β- and γ-CyD derivatives as sensors for detecting organic compounds in aqueous solution.[3–7] In most of these sensoring systems, the complex formation with a guest molecule changes the location of the attached chromophore from inside to outside of the cavity, resulting in a marked change in the spectrum of the chromophore-modified CyDs. They are useful for detecting medium or large sized cyclic compounds such as adamantane derivatives and steroidal compounds. We then want to apply this system for detecting chain compounds like aliphatic alcohols by using α-cyclodextrin (α-CyD) which has an appropriately narrow cavity size, however the chromophores which have been used before were too large to include in the cavity of α-CyD and therefore are not appropriate for constructing sensors for chain compounds.

Thus we have attempted to construct a novel sensoring

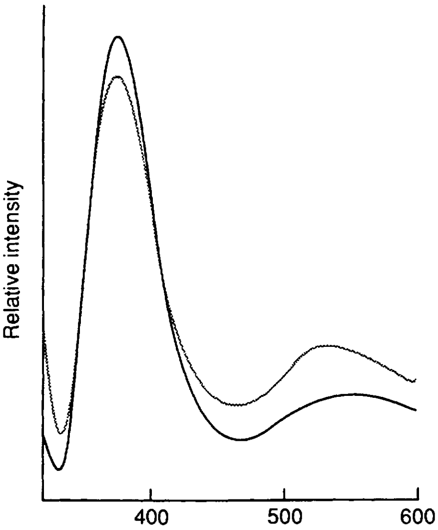


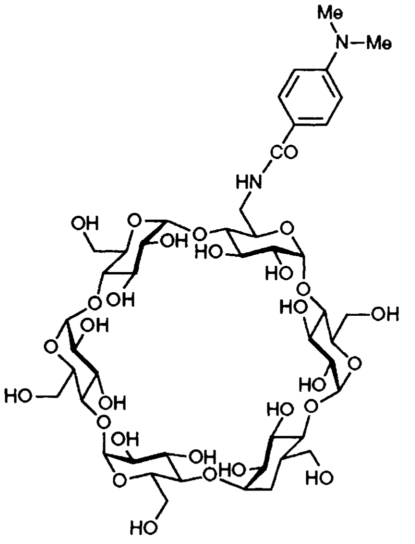
Fig. 1 Fluorescence emission spectra of DMAB–α-CyD (2.5×10^{-5} mol dm^{-3}) in aqueous solution alone (–) and in the presence of n-pentanol (2.5×10^{-3} mol dm^{-3}) (····)

system that changes its fluorescence intensity upon guest binding without inclusion of the attachment in the α-CyD cavity in any process of the sensoring mechanism. *p*-Dimethylaminobenzonitrile (DMABN) and its derivatives show dual fluorescence arising from normal planar (NP) and twisted intramolecular charge transfer (TICT) excited states[8] and it is well known that the position and intensity of TICT emission is very sensitive to the environmental polarity.[9,10] The influence of α-, β- and γ-CyD on a TICT emission of *p*-dimethylaminobenzonitrile has been investigated.[11–14] On this basis, we have prepared an α-CyD derivative in which a *p*-dimethylaminobenzoyl (DMAB) moiety is covalently attached to α-CyD (DMAB–α-CyD) as a novel sensor for detecting chain compounds and have observed the fluorescence responses for aliphatic alcohols. The preparation of DMAB–α-CyD was performed by the reaction of mono-6-deoxy-6-amino-α-cyclodextrin and *p*-dimethylaminobenzoic acid in *N,N*-dimethylformamide below 0 °C in the presence of *N,N*-dicyclohexylcarbodiimide (DCC). The product was identified by ^{1}H NMR spectroscopy and elemental analyses and satisfactory results were obtained.

Table 1 Guest induced NP and TICT emission intensities of DMAB–α-CyD and binding constants

Guests	$\Delta I_{\mathrm{NP}}/I^{0}_{\mathrm{NP}}$	$\Delta I_{\mathrm{TICT}}/I^{0}_{\mathrm{TICT}}$	K/dm^3 mol^{-1}
n-Butanol	−0.027	0.111	300
Isobutanol	−0.014	0.056	—[a]
tert-Butanol	0.000	0.000	—[a]
n-Pentanol	−0.081	0.167	600
Isopentanol	−0.027	0.111	250
tert-Pentanol	−0.014	0.000	—[a]
n-Hexanol	−0.108	0.056	810

[a] The guest-induced variations in the emission were too small to determine the binding constants.



DMAB–α-CyD

Fig. 1 shows the fluorescence emission spectra of DMAB–α-CyD (2.5×10^{-5} mol dm^{-3}) in water alone and in the presence of n-pentanol (2.5×10^{-3} mol dm^{-3}). The excitation wavelength is 310 nm. The spectrum of DMAB–α-CyD alone exhibits peaks at 370 nm (emission from the planar excited state) and 540 nm (emission from TICT excited state). Cox *et al.* asserted that DMABN is included with its cyano protrusion into the cavity of α-CyD but reverse inclusion is unfavourable. In the case of DMAB–α-CyD the situation is different because its DMAB moiety is linked rigidly to an α-CyD unit by an amide bond. Furthermore, the examination of molecular models [Corey–Pauling–Koltun (CPK)] suggests that there exists no possibility for the DMAB moiety to be included. This suggestion was confirmed by the ROESY (rotating frame Overhauser enhancement spectroscopy) spectrum of DMAB–α-CyD (mixing time is 300 ms) *i.e.* there were no cross peaks between the protons of the DMAB moiety and that of the CyDs. Complex formation of DMAB–α-CyD with alcohol decreases NP emission intensity and increases TICT emission intensity. These results indicate that DMAB–α-CyD changes environmental polarity around the DMAB moiety. Therefore the polarity change, which strengthens the TICT emission upon guest binding, may be due to the enhancement of the hydrophobicity around the DMAB moiety. This may arise from the contact between the DMAB moiety and the hydrophobic surface of the included guest in the complex. This feature is consistent with the previous report by Koswer *et al.* that the intensity of TICT emission of DMABN increases with solvent polarity up to $E_T(30)$ value around 46 (acetonitrile) and then decreases with increasing solvent polarity.[9] The values of $\Delta I_{\mathrm{NP}}/I^{0}_{\mathrm{NP}}$ and $\Delta I_{\mathrm{TICT}}/I^{0}_{\mathrm{TICT}}$ were used as sensitivity parameters of DMAB–α-CyD for the guest molecules, where $\Delta I = I^0 - I$ and I^0 and I are the corresponding emission intensities in the absence and presence of guest molecule, respectively. Binding constants of DMAB–α-CyD for guest molecules were obtained from guest-induced variations of the emission intensity at 370 nm by the least-squares curve fitting analysis[15,16] performed using the following Benesi–Hildebrand type equation[17] [eqn. (1)] which holds under the conditions of a large excess of the guest and 1 : 1 host–guest stoichiometry,

$$I_{\mathrm{obs}} = \frac{I_{\mathrm{host}} + I_{\mathrm{com}} K[\mathrm{guest}]_0}{1 + K[\mathrm{guest}]_0} \tag{1}$$

where I is fluorescence intensity, I_{obs} for the sample, I_{host} for the host alone and I_{com} for the complex. K is the binding constant of the complex formation and $[\mathrm{guest}]_0$ is the initial total concentration of the guest. The plots of I_{obs} against $[\mathrm{guest}]_0$ coincided with the theoretical curve that was obtained by eqn. (1) and confirmed the 1 : 1 stoichiometry. The results are summarized in Table 1.

For two series of alcohol, C_4H_9OH and $C_5H_{11}OH$, the sensitivity of DMAB–α-CyD are in the order of normal > iso > *tert*. The results are consistent with the conclusion drawn by the examination of the molecular models (CPK) that n-alkanols are easy to include in the α-CyD cavity of DMAB–α-CyD in comparison with the branched alkanols. The fluorescence variations of n-alkanols detected by $\Delta I_{\mathrm{NP}}/I^{0}_{\mathrm{NP}}$ are in the order n-butanol < n-pentanol < n-hexanol, but those detected by $\Delta I_{TICT}/I^0_{TICT}$ are in the order n-butanol < n-hexanol < n-pentanol. The order of the binding constants of these alcohols is the same as that of $\Delta I_{NP}/I^0_{NP}$, but different from that of $\Delta I_{TICT}/I^0_{TICT}$. At present, there is no simple theoretical relationship between binding constant and $\Delta I_{NP}/I^0_{NP}$ or $\Delta I_{TICT}/I^0_{TICT}$ values. The guest responsive fluorescence behaviour of DMAB–α-CyD demonstrates that the TICT fluorescence as well as the NP one is useful for detecting chain compounds such as n-butanol, n-pentanol and n-hexanol. The study on the detail of the location and the orientational features of the DMAB moiety in DMAB–α-CyD and in the complexes is now under way.

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References

1 M. L. Bender and M. Komiyama, *Cyclodextrin Chemistry*, Springer-Verlag, Berlin, 1978.

2 J. Szejtli, *Cyclodextrin Technology*, Kluwer Academic Publishers, Dordrecht, 1988.

3 A. Ueno, I. Suzuki and T. Osa, *Anal. Chem.*, 1990, **62**, 2461.

4 A. Ueno, S. Minato, I. Suzuki, M. Fukusima, M. Ohkubo, T. Osa, F. Hamada and K. Murai, *Chem. Lett.*, 1990, 605.

5 M. Fukushima, T. Osa and A. Ueno, *J. Chem. Soc., Chem. Commun.*, 1991, 15.

6 S. Minato, T. Osa and A. Ueno, *J. Chem. Soc., Chem. Commun.*, 1991, 107.

7 A. Ueno, T. Kuwabara, A. Nakamura and F. Toda, *Nature*, 1992, **356**, 136.

8 W. Rettig, *Angew. Chem., Int. Ed. Engl.*, 1986, **25**, 971.

9 E. M. Koswer and H. Dodiuk, *J. Am. Chem. Soc.*, 1976, **98**, 924.

10 G. Wermuth and W. Rettig, *J. Phys. Chem.*, 1984, **88**, 2729.

11 G. S. Cox, P. J. Hauptman and N. J. Turro, *Photochem. Photobiol.*, 1984, **39**, 597.

12 A. Nag and K. Bhuttacharayya, *Chem. Phys. Lett.*, 1988, **151**, 474.

13 A. Nag, R. Dutta, N. Chattopadhyay and K. Bhuttacharayya, *Chem. Phys. Lett.*, 1989, **157**, 83.

14 A. Nag and K. Bhuttacharayya, *J. Chem. Soc., Faraday Trans.*, 1990, **86**, 53.

15 S. Hamai, *J. Phys. Chem.*, 1989, **93**, 2074.

16 A. Nakamura, K. Saitoh and F. Toda, *Chem. Phys. Lett.*, 1991, **187**, 110.

17 H. A. Benesi and J. H. Hildebrand, *J. Am. Chem. Soc.*, 1949, **71**, 2703.