Dual emission of a bis(pyrene)-functionalized, perbenzylated β-cyclodextrin†

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A bis(pyrene)-functionalized β-cyclodextrin (**1**) has been prepared in two steps from perbenzylated β-cyclodextrin. This compound shows dual emission properties, which arise from the pyrenyl chromophores. Upon excitation of **1** at 355 nm, monomer blue fluorescence (386, 407 and 428 nm) is observed in DMSO solution, whereas excimer green fluorescence (477 nm) is seen upon addition of $\geq$ 20 vol% water in DMSO. This suggests that modified β-cyclodextrin **1** changes its shape in response to the environment. The sensing properties of **1** towards carboxylic acids and alcohols were investigated in H_2O–DMSO (80 : 20 v/v). Monomer fluorescence is restored selectively by medium length normal carboxylic acids, such as enanthic acid (C_7) found in rancid oils and capric acid (C_{10}), while both monomer and excimer emissions are enhanced by homologous alcohols, such as 1-heptanol, used in cosmetics and 1-decanol. Remarkably, bulkier substrates, such as *tert*-butyl alcohol or 1-adamantylcarboxylic acid are not detected.

Introduction

Cyclodextrins (CDs) are naturally-occurring, cone-shaped hollow molecules made from six (α-CD), seven (β-CD), and eight (γ-CD) α-1,4-connected D-(+)-glucopyranosyl subunits, which can include various hydrophobic organic molecules inside their cavity, in aqueous medium or water–solvent mixtures.[1] β- and γ-cyclodextrins modified with fluorophores tethered on the narrow rim have been shown to act as luminescent sensors for compounds of biological and environmental interest, such as steroids, terpenes, (chloro)phenols and other aromatic molecules.[2] In several instances, the signalling event relies on the dual emission of reporter groups able to form excimers,[3] such as those based on naphthyl,[4] dansyl,[5] and pyrenyl[6] fluorophores, the latter being of particular relevance to the present work.

Pyrene itself can show excimer fluorescence in the presence of γ-CD,[7] but not β-CD,[8] an observation that has been analyzed in terms of different stoichiometries of the pyrene⊂CD inclusion complexes: in the case of γ-CD, while excimer fluorescence originates from the 2 : 2 complex,[9a,c] monomer emission is due to the 1 : 1 adduct;[9b] in the case of smaller β-CD, monomer emission is mainly due to the 1 : 2 complex,[9b,10b] but partial inclusion of pyrene in 1 : 1 complexes has been also observed.[10]

Pyrene excimer fluorescence can also be shown by cyclodextrins equipped with two pyrene luminophores.‡ Bis(pyrenyl)/CD conjugates reported so far are built either on γ-CD[6a,d] or β-CD.[6b,c,e] The construction of bichromophoric CDs usually involves ditosylation of the primary (at glucose 6-C) hydroxyl groups of the narrow rim as first step. Applied to β-CD, this reaction leads to three positional isomers noted 6A6B, 6A6C and 6A6D,§ which can be separated by column chromatography.[12] Elegant alternatives are regiospecific disulfonate capping,[13] and, as reported recently, regioselective deprotection of perbenzylated CDs, using an excess of DIBAL-H.[14] In the latter conditions, perbenzylated β-CD leads to the 6A6D diol exclusively, which can be further functionalized and deprotected by catalytic hydrogenolysis.[14b,c]

The work reported here uses this latter strategy to prepare a bis(pyrene)-functionalized, perbenzylated β-CD, whose dual emission properties in water–DMSO mixtures in the absence and presence of various substrates are described.

Results and discussion

Synthesis

The three-step preparation of **1** from β-CD is shown in Scheme 1. At first, β-cyclodextrin was reacted with benzyl chloride at room temperature in DMSO in the presence of excess NaH to give perbenzylated β-cyclodextrin **2**.[14b,c,15] Subsequent regiospecific debenzylation with DIBAL-H in toluene at 30 °C, as reported, afforded diol **3**.[14a,b] Finally, reaction of an excess of 1-hydroxypyrene[16] with diol **3** in Mitsunobu reaction conditions[17] (DIAD, PPh_3, THF, 0 °C to RT) afforded target modified β-cyclodextrin **1** in 90% yield after chromatography. Two sets of peaks were observed by

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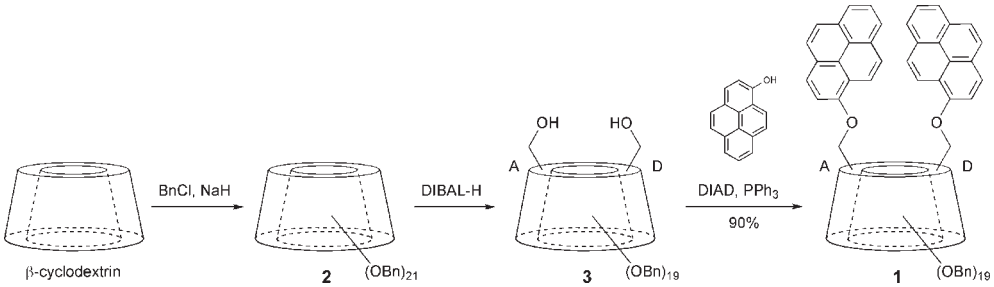
† Electronic supplementary information (ESI) available: ^{1}H NMR of **1** (details of assignment, ^{1}H/^{1}H COSY, TOCSY and ROESY), ^{1}H/^{13}C correlations (HSQC and HMBC), electronic absorption spectra of **1** in H_2O–DMSO mixtures, fluorescence spectra of **1** in the presence of different analytes, photographs showing the color of luminescence of **1** in various conditions. See DOI: 10.1039/b803144d

‡ Remarkably, γ-CD with a single tethered pyrenyl group can form association dimers, while self-inclusion complexes, in which both dangling pyrenyl arms reside inside the CD cavity, can be observed in the case of doubly functionalized systems. These complexes are usually detected by excimer fluorescence.[4a,11]

§ The seven sugar subunits of β-CD are labelled A–G, see Scheme 2.



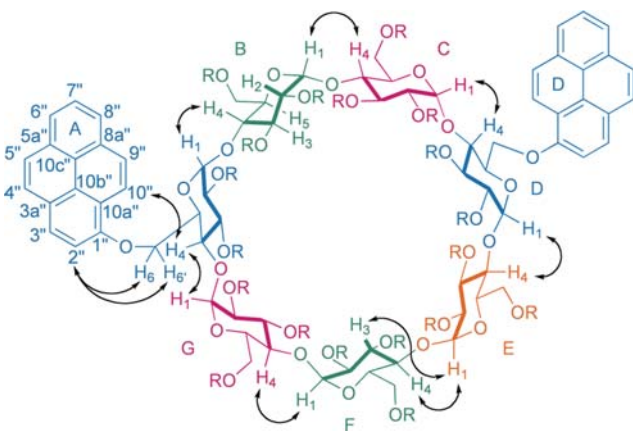
Scheme 1 Synthesis of **1**. The benzyl groups are distributed on both sides of the CD ring (5 upper, 14 lower).

MALDI-TOF mass spectrometry. They correspond to the Na^+ (m/z = 3269.48) and K^+ (m/z = 3285.46) adducts, respectively.

^{1}H NMR Spectroscopy

The solution structure of **1** was investigated by ^{1}H (600 MHz) and ^{13}C (151 MHz) NMR spectroscopy using a combination of 2D techniques (COSY, TOCSY, ROESY, HSQC and HMBC, see Fig. S1–S8, ESI†).[18] The structural formula of **1** is represented in Scheme 2, with proton labelling and selected NOE correlations indicated. The assigned proton spectrum in d^6-acetone, which is better resolved than in $CDCl_3$, CD_2Cl_2 and particularly, d^6-DMSO solutions (Fig. S9, ESI†), is represented in Fig. 1 and S10 (ESI†). Comparison with the spectrum of precursor diol **3** (Fig. S11, ESI†) illustrates the scattering effect of the anisotropic pyrenyl substituents on the sugar β-CD protons. Due to the C_7 symmetry of the parent β cyclodextrin, the two pyrenyl moieties, which are placed in the A and D positions, are not equivalent, however they could not be differentiated from each other. Of the pyrenyl protons, only $2''_{A,D}$-H and $10''_{A,D}$-H, which are the closest to the oxygen atoms connecting the chromophores to the $6_{A,D}$-C of the β-CD platform show significant shifts by comparison with 1-hydroxypyrene (−0.18 and 0.12 ppm, respectively) (Fig. S11, ESI†).

The ^{1}H NMR spectrum of **1** in the high-field region is very intricate due to the asymmetry of the molecule. Of the 87 different aliphatic protons, all the sugar protons (49) could be assigned within the pairs (A, D), (B, F) and (C, G), and the isolated subunit E. The other (38) belong to the 19 benzylic diastereotopic proton pairs, as the one giving rise to the AB signal centered at 4.32 ppm (J_{AB} = 12.3 Hz, $\Delta\nu$ = 12.7 Hz). Assignment of the aliphatic protons is initiated with a ROESY experiment (Fig. 2 and S3, ESI†). The detailed map of Fig. 2 shows through space correlations between $10''_{A,D}$-H (respectively, $2''_{A,D}$-H) of the pyrenyl subunits and $4_{A,D}$-H (respectively $6_{A,D}$-H and $6'_{A,D}$-H) of the sugars A and D, which provides starting points for the β-CD framework. Correlations between two consecutive sugar subunits involve protons 1-H and 4-H, respectively.[18b] They are also shown in Fig. 2, with the exception of the correlations 1_A-H/4_B-H and 1_D-H/4_E-H, which are very weak (Fig. S3, ESI†). The corresponding through-bond correlations involving 1-C (resp. 4-C) and 4-H (resp. 1-H) are also clearly seen in the HMBC spectrum (Fig. S6 and S8, ESI†). Noteworthy, in addition to the NOE correlation 4_F-H/1_E-H, sugar F shows the correlation 3_F-H/1_E-H. As expected from earlier studies, the doublets attributed to 1-H are observed in the downfield region (5.5–5.1 ppm).[14b] The dd signals of 2-H, which are coupled to 1-H and 3-H, and the broad doublets of 6′-H are observed in the upfield part of the aliphatic region (3.35–3.85 ppm). All the other sugar protons resonate between 4.30 and 3.85 ppm, with the exception of $4_{A,D}$-H, $5_{A,D}$-H, and diastereotopic $6_{A,D}$-H and $6'_{A,D}$-H of the sugars A and D bearing the pyrenyl chromophores, which resonate at lower fields. This deshielding (which is >1 ppm for $6'_{A,D}$-H) is due to the fact that these protons are located near the edge of the pyrenyl aromatic rings, an observation consistent with the ROESY studies.



Scheme 2 Structural formula of **1** (R = Bn) viewed from the lower rim with sugar nomenclature and atom numbering detailed for the pyrenyl substituents and sugar B. The double ended arrows show key NOE correlations.

Conformational analysis of wide-rim perbenzylated CDs is well documented.[19] In particular, compounds that carry 6-C substituents commensurate with the internal cavity do not display exclusively the conical shape of the native CDs. For example, whereas perbenzylated β-CD itself is conical (C_7 symmetry), its analogue that bears naphthoyl groups on the narrow rim instead exists as a 1 : 1 equilibrium mixture of C_7 symmetrical and unsymmetrical (C_1) conformers in $CDCl_3$ at room temperature. The C_1 conformer results from internal rotation of one glucopyranose ring around its 1,4 axis, leading to inclusion of the corresponding naphthoyl substituent inside the cyclodextrin cavity. In the case of native β-CD, sugar 3-H and 5-H are located internally, whereas 1-H, 2-H and 4-H point outside. The fact that all through space NOE correlations between 1-H and 4-H of consecutive sugars are observed in **1** shows that this modified cyclodextrin has nearly the ideal β-CD torus shape, the additional NOE correlation

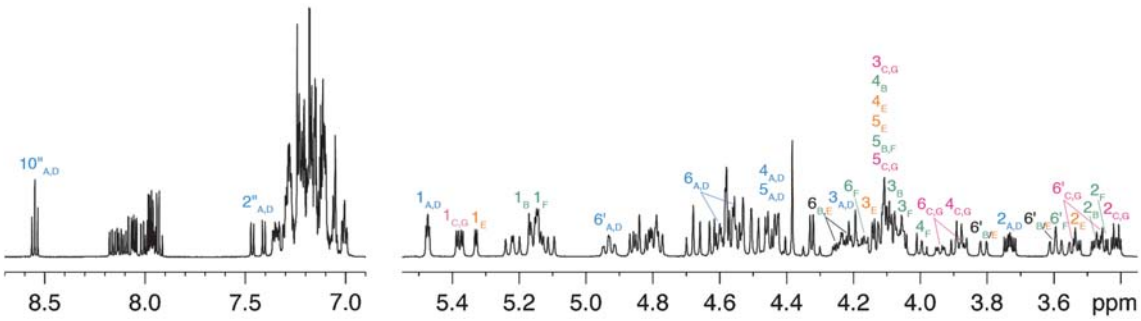


Fig. 1 ^{1}H NMR spectrum (d^{6}-acetone, 600 MHz) of **1**. The aromatic region is detailed in Fig. S10 (ESI†).

3_F-H/1_E-H suggesting a small distortion of the torus at the hinge between sugar E and sugar F. The NOE correlations $10''_A$-H/4_A-H (resp. $10''_D$-H/4_D-H), $2''_A$-H/6_A-H ($2''_D$-H/6_D-H) and $2''_A$-H/$6'_A$-H ($2''_D$-H/$6'_D$-H) observed between the pyrenyl and sugars A (resp. D) subunits show that the luminophores point outside the β-CD cavity and are positioned equatorially with respect to the β-CD torus, the 6,6′-H proton pair pointing upwards. Therefore, the pyrenyl chromophores are efficiently separated from each other by the β-CD platform in the moderately polar solvent acetone.

UV-visible absorption and luminescence spectroscopy

The UV-Vis absorption spectrum of **1** in DMSO (Fig. S12, ESI†) is characterized by the sharp absorption of the benzyl substituents at 281 nm (ε = 95 500 dm^3 mol^{-1} cm^{-1}) and the broad, albeit structured, manifold of the pyrenyl subunits in the near UV, with maxima at 348 (ε = 52 000 dm^3 mol^{-1} cm^{-1}) and 355 nm (ε = 51 700 dm^3 mol^{-1} cm^{-1}). Sharp satellite absorptions are observed at 365 (ε = 35 500 dm^3 mol^{-1}cm^{-1}) and 384 nm (ε = 21500 dm^3 mol^{-1} cm^{-1}). The magnitudes of the molar absorption coefficients are consistent with the double functionalization of β-CD with the pyrenyl chromophore.[20]

When excited at the maximum of pyrene absorption (355 nm), dilute (10^{-6} mol dm^{-3}) solutions of **1** in DMSO show the strong fluorescence of the pyrenyl luminophores, with emission maxima at 386, 407 and 428 nm. However, upon addition of increasing amounts of water, this emission decreases at the expense of the characteristic excimer emission of pyrene at 477 nm (Fig. 3). As shown in the inset at four different wavelengths, the monomer (386, 407 and 428 nm) and excimer (477 nm) emission intensities are approximately constant for concentrations of water in DMSO below 17%. Then, between 18 and 20%, the monomer emission intensity decreases abruptly. Finally, above ≈22% of water, the monomer and excimer emissions are no longer significantly changed. The water-tuned emission of **1** in DMSO–water mixtures is illustrated by the photograph of Fig. S13 (ESI†) taken under UV-lamp irradiation at 365 nm, which shows that increasing the amount of water changes the color of the emitted light from blue to green. As can be anticipated from Fig. 3, blue–green emission is observed for solutions containing ≈18% of water.

Absorption changes at various selected water concentrations are shown in Fig. S14 (ESI†). Unexpectedly, the spectra obtained for pure DMSO and water–DMSO (80 : 20 v/v)

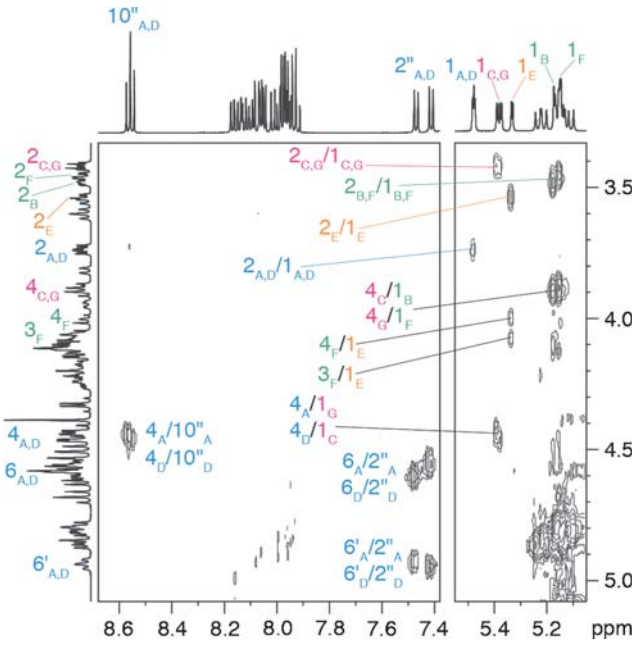


Fig. 2 Portions of the ROESY ^{1}H NMR spectrum of **1** (d^{6}-acetone, 600 MHz, mixing time: 300 ms).

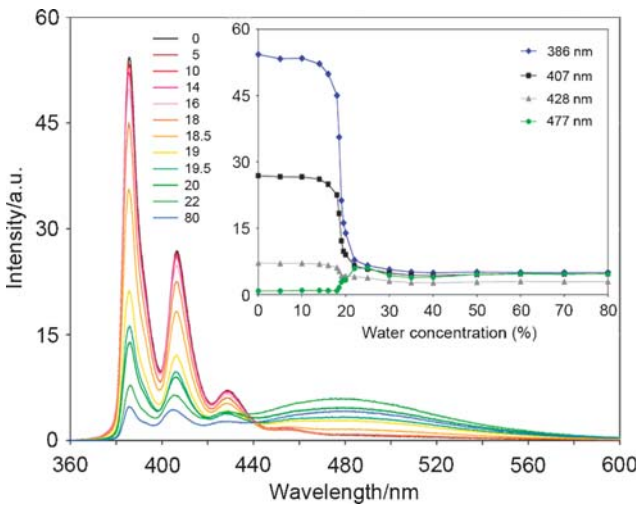


Fig. 3 Fluorescence spectra of **1** (1.0×10^{-6} mol dm^{-3}, 25 °C) at various concentrations of water in DMSO solution. The inset shows intensities changes at 386, 407, 428 and 477 nm.

solutions are very similar with each other, which indicates that the pyrenyl residues do not show electronic interaction in the ground state. However, in the transition region of fluorescence regime (18–20% H_2O), the absorption spectra are obscured by a background residual absorption, which gradually disappears as the concentration of water is increased, becoming negligible above 40% H_2O. The largest changes are observed at $\approx$19.5% of water, where the absorption band of the benzyl substituents is broadened and blue-shifted by 2 nm. In fact, careful examination of the corresponding solutions shows the presence of turbidity, which is detected to the naked eye by light scattering.

Switching of the monomer/excimer dual emission of the pyrenyl fluorophores can, in principle, be rationalized in terms of hydrophobic effects. In pure DMSO solution, as demonstrated in d^6-acetone, **1** is likely to have an open form too, in which the pyrenyl luminophores are distant form each other, and therefore display the monomer-type emission.¶ This situation does not change until the proportion of water in DMSO reaches $\approx$17%. At 80% of water, the hydrophobic pyrenyl moieties of **1** reduce their exposure to the solvent most likely by folding at the upper rim of the cyclodextrin platform, the resulting pyrenyl "dimer" being too bulky to penetrate the hydrophobic β-cyclodextrin cavity. Moreover, it is reasonable to assume that the five upper-rim benzyl substituents fold around the pyrene dimer, and the fourteen lower-rim benzyl substituents curl up at the lower opening of the cyclodextrin cavity to further reduce the availability of these aromatic surfaces for interaction with the wet solvent. Unfortunately, **1** was not soluble enough in $\geq$ 20 vol% H_2O in DMSO to verify these hypotheses by ^{1}H NMR spectroscopy. Between these extremes, the situation is more complex, especially in the 17–22% concentration range, where the formation of aggregates is likely to occur.

In summary, modified β-cyclodextrin **1** is a dual light emitter controlled by water concentration in DMSO. Remarkably, the transition between the two emission modes occurs in quite a narrow water concentration range (17–20%), making this compound a genuine on/off switch. Interestingly, the fluorescence properties of β-cyclodextrin **1** in water–DMSO mixtures nicely complement those of a reported bis(pyrene)-modified β-cyclodextrin dimer, which shows maximum excimer emission in DMSO–water (90 : 10 v/v).[6e]

Sensing properties of 1 by luminescence

The possibility to recover the monomer fluorescence by addition of potential guest species to solutions of modified β-CD host **1** showing excimer fluorescence, was next investigated. The solvent mixture water–DMSO (80 : 20 v/v) was selected, as it favors hydrophobic interactions while still allowing to solubilize **1** in the micromolar concentration range. A variety of organic compounds (Chart S1, ESI†) were screened qualitatively, by observation of 2×10^{-6} mol dm^{-3} solutions of **1** under the UV lamp at 365 nm. In particular, 6-chloro-1-hexanol, and the linear aliphatic 1-heptanoic and 1-decanoic carboxylic acids changed the color of fluorescence of **1** from green to blue, whereas the corresponding alcohols (1-heptanol and 1-decanol) produced brighter luminescence. These
compounds were selected for detailed spectroscopic studies.

As shown in Fig. 4, upon addition of increasing amounts of 1-heptanoic acid in acidic (0.04% HCl) water–DMSO (80 : 20 v/v) mixture to 10^{-6} mol dm^{-3} solutions of **1**, the monomer emission gradually develops at the expense of the excimer emission, which nearly completely vanishes. Visualization of the phenomenon under the UV lamp is shown in Fig. S15 (ESI†). Similar results were obtained with 1-decanoic acid and 6-chloro-1-hexanol (Fig. S16 and S17, ESI†). However, in the case of 1-heptanol and 1-decanol both monomer fluorescence and excimer emission intensities increase concomitantly. In addition, the excimer band undergoes a slight red shift ($\approx$8 nm). This is illustrated in Fig. 5 for 1-heptanol and Fig. S18 (ESI†) for 1-decanol. The fluorescence spectra of 10^{-6} mol dm^{-3} solutions of **1** in the presence of the other compounds of Chart S1 at 0.1 mol dm^{-3} concentrations (1,4-benzenedimethanol, 1-adamantylcarboxylic acid and myristic acid excepted, which were employed at 5.0×10^{-2}, 2.0×10^{-3}, and 5.0×10^{-4} mol dm^{-3}, respectively) are collected in Fig. S19 (ESI†). Cyclohexanol produces very similar features as 1-heptanol, but without luminescence enhancement, and malonic acid has practically no effect. The other compounds simply quench the emission intensity of **1** to various extents. Among these are short chain linear 1-butanoic acid and 1-butanol, compounds with a bulkier, ball-like shape such as benzoic and 1-adamantylcarboxylic acids, *tert*-butanol and phenol. These observations suggest that the dual fluorescence changes of β-CD **1** are governed by host–guest effects. Unfortunately, the numerical analysis of the fluorescence spectra by using realistic binding models, such as that involving a 1 : 1 ratio between host and guest, did not give reasonable results for the association constants. This would suggest that aggregates involving substrate and receptor

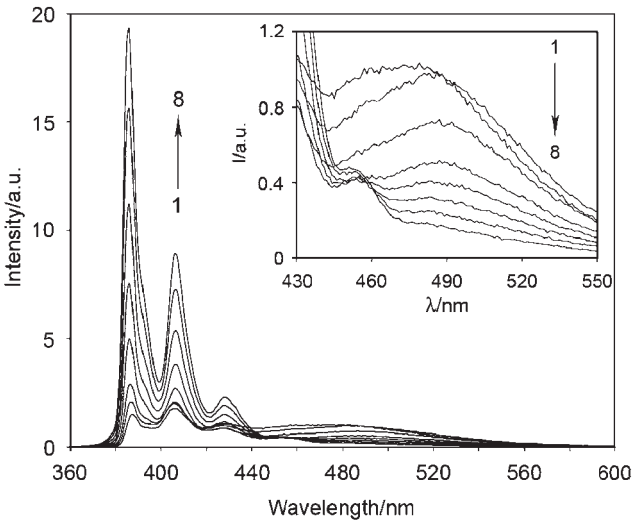


Fig. 4 Fluorescence spectra of **1** (1.0×10^{-6} mol dm^{-3}) upon addition of 1-heptanoic acid ((1) 0, (2) 5.0×10^{-3}, (3) 1.0×10^{-2}, (4) 1.5×10^{-2}, (5) 2.0×10^{-2}, (6) 2.5×10^{-2}, (7) 3.0×10^{-2}, (8) 3.5×10^{-2} mol dm^{-3}) in acidic (0.04% HCl) H_2O–DMSO (80 : 20 v/v), 25 °C. The inset shows the excimer emission.

¶ **1** shows blue, monomer-like fluorescence in acetone.

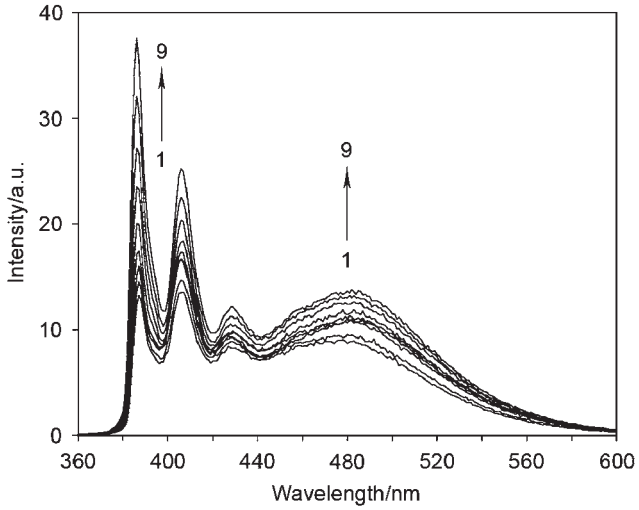


Fig. 5 Fluorescence spectra of **1** (1.0×10^{-6} mol dm^{-3}) upon addition of 1-heptanol ((1) 0, (2) 5.0×10^{-3}, (3) 1.0×10^{-2}, (4) 1.5×10^{-2}, (5) 2.0×10^{-2}, (6) 2.5×10^{-2}, (7) 3.0×10^{-2}, (8) 3.5×10^{-2}, (9) 4.0×10^{-2} mol dm^{-3}) in H_2O–DMSO (80 : 20 v/v) at 25 °C.

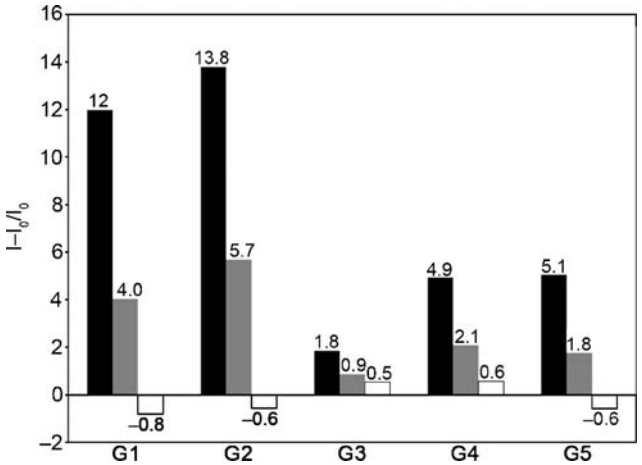


Fig. 6 Sensitivity parameters of host **1** (1.0×10^{-6} mol dm^{-3}) with guests **G1–G5** at 386 (black bars), 407 (gray bars) and 477 (white bars) nm in H_2O–DMSO (80 : 20 v/v) at 25 °C. (i) 3.5×10^{-2} mol dm^{-3} 1-heptanoic acid, **G1**–0.04% HCl; (ii) 1.2×10^{-3} mol dm^{-3} 1-decanoic acid, **G2**–0.04% HCl; (iii) 4.0×10^{-2} mol dm^{-3} 1-heptanol, **G3**; (iv) 1.4×10^{-3} mol dm^{-3} 1-decanol, **G4** and (v) 3.0×10^{-2} mol dm^{-3} 6-chloro-1-hexanol, **G5**.

molecules are formed. In addition, **1** being a perbenzylated β-CD, its binding properties in water-rich environment may differ significantly from those of native CDs, especially in view of the expected steric crowding of its openings (see the previous section). This observation is supported by the fact that
1-adamantylcarboxylic acid, which shows the highest binding constant with β-cyclodextrin,[1c] has practically no influence on the dual fluorescence of **1**.

The different effects of 1-heptanoic and 1-decanoic acids, and 6-chloro-1-hexanol on the one hand (enhancement of monomer emission and depletion of excimer emission), 1-heptanol and 1-decanol on the other hand (enhancement of monomer and excimer emission accompanied by a red shift of the latter), can both result from interaction of these two groups of guests with the β-CD host **1**, but in different manners. As a matter of fact, the direct anchoring of the pyrenyl substituents to the small rim of **1** makes their emission behavior very sensitive to the nature (shape and flexibility) of the substrate that binds to β-CD **1**: excimer formation can be suppressed by distortion of the cyclodextrin backbone, while enhancement of emission can be brought about by rigidification of the complex by comparison with the free host. Indeed, enhancement of pyrene fluorescence has been noted for ternary complexes between β-CD, pyrene, and alcohols[21a] or amino acids.[21b]

In order to quantify the sensing ability of **1**, $\Delta I/I_0$ ratios ($\Delta I = I - I_0$, where I and I_0 represent the emission intensities of **1** with and without added analyte, respectively) were measured at three different wavelengths (386 and 407 nm for the monomer emission, and 477 nm for the excimer emission), and were used as sensitivity parameters[4a] for the acids and alcohols mentioned above (Fig. 6). This shows that 1-heptanoic and 1-decanoic acids are detected by β-CD **1** with higher sensitivity than the corresponding alcohols. In summary, modified cyclodextrin β-CD **1** is quite a selective fluorescent sensor for 1-heptanoic (enanthic) acid, a contributor to the odour of some rancid oils,[22] while 1-butanoic acid, found in rancid butter, is not detected.

Conclusion

An interesting feature of bis(pyrene)-functionalized perbenzylated β-CD **1** is the quasi-direct anchoring of the pyrenyl luminophores to the cyclodextrin backbone. This results in effective transduction of conformational changes that are triggered by the environment (*e.g.* solvent polarity or presence of analytes) into switching of luminescence regime. However, the phenomena that come into play are not as straightforward as it may appear from this picture and most probably involve complex molecular assemblies. Future work in this context will entail light scattering studies and comparison with unprotected cyclodextrins, since the inclusion properties of these systems in aqueous solutions are well established.

Experimental

General

β-Cyclodextrin was dried under vacuum over P_2O_5 prior to use. All other reagents were used without further purification. Modified β-CDs **2**[14b,c,15] and **3**,[14] and 1-hydroxypyrene[16] were prepared according to literature methods. Solvents used in the syntheses were dried and distilled under standard conditions. All reactions were performed under a nitrogen atmosphere. ^{1}H and ^{13}C NMR spectra were recorded on a Bruker AVANCE 600 instrument. Chemical shifts are referenced downfield from Me_4Si and coupling constants are given in Hz. Mass spectra were recorded on a Bruker ProFLEX III spectrometer (MALDI/TOF) using dithranol as the matrix. Elemental analyses were performed on a Fisons EA 1108 CHNS instrument. UV-visible spectra were recorded on either a Varian Cary 5

or a Cary 50 spectrophotometer and photoluminescence spectra were collected on a Fluorolog-III Horiba-Jobin-Yvon spectrofluorimeter.

1-Hydroxypyrene

δ_H (600 MHz; d^6-acetone; Me_4Si) 7.62 (1 H, d, *J* 8.4, 2-H), 7.92 (1 H, d, *J* 9.0, 5-H), 7.98 (1 H, t, *J* 7.8, 7-H), 8.02 (1 H, d, *J* 9.0, 4-H), 8.06 (1 H, d, *J* 9.3, 9-H), 8.11 (1 H, d, *J* 8.4, 3-H), 8.14 (1 H, br d, *J* 7.8, 6-H or 8-H), 8.15 (1 H, br d, *J* 7.8, 6-H or 8-H), 8.43 (1 H, d, *J* 9.0, 10-H) and 9.44 (1 H, br m, OH); δ_C (151 MHz; d^6-acetone; Me_4Si) 113.9 (2-C), 119.5 (10a-C), 122.2 (10-C), 124.6 (6-C or 8-C), 124.9 (6-C or 8-C), 125.1 (5-C), 125.5 (10c-C), 125.9 (3a-C), 126.6 (9-C), 126.8 (3-C), 126.9 (10b-C), 127.0 (7-C), 128.3 (4-C), 132.8 (d, 5a-C and 8a-C) and 152.7 (1-C).

Heptakis(2,3-di-*O*-benzyl)-6^B,6^C,6^E,6^F,6^G-penta-*O*-benzyl-β-cyclodextrin (3)

δ_H (600 MHz; d^6-acetone; Me_4Si) 3.43–3.49 (4 H, m, 2-H), 3.44 (1 H, dd, *J* 9.0 and 3.0, 2-H), 3.52 (1 H, dd, *J* 9.3 and 3.3, 2-H), 3.54 (1 H, dd, *J* 9.0 and 3.6, 2-H), 3.57 (0.3 H, dd, *J* 12.6 and 4.8, 6-H),‖ 3.58 (0.3 H, dd, *J* 12.6 and 4.8, 6-H),‖ 3.68 (1 H, dd, *J* 11.4 and 1.2, 6′-H), 3.71 (1 H, dd, *J* 11.4 and 1.2, 6′-H), 3.72 (1 H, dd, *J* 10.2 and 1.2, 6′-H), 3.73 (1 H, dd, *J* 11.4 and 1.2, 6′-H), 3.74 (1 H, dd, *J* 10.8 and 1.2, 6′-H), 3.82–3.87 (2 H, m, 6′$_{A/D}$-H), 3.91–4.01 (2 H, m, 5-H; 2 H, m, 6-H; 7 H, m, 4-H), 4.01–4.11 (5 H, m, 5-H; 7 H, m, 3-H), 4.11–4.18 (5 H, m, 6-H), 4.42–4.62 (22 H, m, PhC*H*), 4.66 (1 H, d, *J* 12.6, 2-PhC*H*), 4.68 (1 H, d, *J* 12.6, 2-PhC*H*), 4.74 (1 H, d, *J* 10.8, PhC*H*), 4.75 (1 H, d, *J* 11.4, PhC*H*), 4.75 (1 H, d, *J* 10.8, PhC*H*), 4.76 (1 H, d, *J* 10.2, PhC*H*), 4.79 (2 H, d, *J* 10.8, PhC*H*), 4.80 (1 H, d, *J* 10.8, PhC*H*), 4.98 (1 H, d, *J* 10.8, PhC*H*), 5.05 (1 H, d, *J* 11.4, PhC*H*), 5.12 (1 H, d, *J* 10.2, PhC*H*), 5.14 (1 H, d, *J* 10.2, PhC*H*), 5.16 (1 H, d, *J* 10.8, PhC*H*), 5.16 (1 H, d, *J* 10.8, PhC*H*), 5.17 (1 H, d, *J* 10.8, PhC*H*), 5.23 (3 H, d, *J* 3.6, 1-H), 5.24 (1 H, d, *J* 3.6, 1-H), 5.30 (1 H, d, *J* 3.6, 1-H), 5.40 (1 H, d, *J* 3.0, 1-H), 5.47 (1 H, d, *J* 3.6, 1-H), 7.05–7.40 (95 H, m, C_6H_5); δ_C (151 MHz; d^6-acetone; Me_4Si) 62.21 (1 C, 6$_{A,D}$-C), 62.29 (1 C, 6$_{A,D}$-C), 70.27 (1 C, 6-C), 70.30 (1 C, 6-C), 70.35 (2 C, 6-C), 70.39 (1 C, 6-C), 72.51 (2 C, 5-C), 72.60 (1 C, 5-C), 72.63 (2 C, 5-C), 73.13 (PhCH), 73.18 (PhCH), 73.23 (PhCH), 73.30 (PhCH), 73.38 (1 C, 5-C), 73.44 (1 C, 5-C), 73.70 (PhCH), 73.72 (PhCH), 73.77 (PhCH), 73.78 (PhCH), 75.67 (PhCH), 75.79 (PhCH), 75.85 (PhCH), 76.01 (PhCH), 76.04 (PhCH), 76.22 (PhCH), 76.26 (PhCH), 77.36 (1 C, 4-C), 78.05 (1 C, 4-C), 79.33 (1 C, 4-C), 79.71 (1 C, 2-C or 4-C), 79.76 (1 C, 2-C or 4-C), 79.80 (1 C, 2-C or 4-C), 79.93 (1 C, 2-C or 4-C), 79.98 (1 C, 2-C or 4-C), 80.18 (2 C, 2-C or 4-C), 80.22 (1 C, 2-C or 4-C), 80.29 (2 C, 2-C or 4-C), 80.38 (1 C, 2-C or 4-C), 81.45 (2 C, 3-C), 81.77 (1 C, 3-C), 81.81 (1 C, 3-C), 81.89 (1 C, 3-C), 81.95 (1 C, 3-C), 82.08 (1 C, 3-C), 98.17 (1 C, 1-C), 98.37 (1 C, 1-C), 98.81 (2 C, 1-C), 98.84 (1 C, 1-C), 98.94 (1 C, 1-C), 99.03 (1 C, 1-C), 127.61, 127.63, 127.67, 127.69, 127.71, 128.06, 128.07, 128.10, 128.12, 128.15, 128.16, 128.18, 128.20, 128.23, 128.26, 128.33, 128.38, 128.40, 128.41, 128.53, 128.56, 128.57, 128.59, 128.66, 128.67, 128.71, 128.76, 128.77, 128.87, 128.91, 129.08 (Ar-CH), 139.46, 139.50, 139.55, 139.62, 139.65, 139.66, 139.70, 139.72, 139.75, 140.32, 140.38, 140.40, 140.49, 140.56, 140.59 (Ar quaternary C).

‖ In d^6-acetone, protons 6$_{A,D}$ show exchange signals with the two dd at 3.57 and 3.58 ppm.

6^A,6^D-Dipyrenyl-2^{A-G},3^{A-G},6^B,6^C,6^E,6^F,6^G-nonadecakis-*O*-benzyl-β-cyclodextrin (1)

A solution of **3** (1.0 g, 0.35 mmol) and 1-hydroxypyrene (0.380 g, 1.76 mmol) in THF (5 mL) was added dropwise to a stirred solution of DIAD (225 μL, 1.07 mmol) and triphenylphosphine (0.276 g, 1.05 mmol) in THF (5 mL) at 0 °C. The resulting mixture was stirred for 3 h at 0 °C and then allowed to warm to room temperature. After 2 days stirring, the solvent was removed with a rotary evaporator. Column chromatography on silica gel (1 : 4 EtOAc–heptane) afforded **1** (1.04 g, 90% yield) as a colorless solid (Found: C, 75.72; H, 6.28. $C_{207}H_{200}O_{35}$ requires C, 76.55; H, 6.21%); δ_H (600 MHz; d^6-acetone; Me_4Si) 3.41 (1 H, dd, *J* 9.3 and 3.3, 2$_C$-H or 2$_G$-H), 3.42 (1 H, dd, *J* 9.6 and 3.6, 2$_C$-H or 2$_G$-H), 3.45 (1 H, dd, *J* 9.3 and 3.3, 2$_F$-H), 3.47 (1 H, br dd, *J* 10.2, 6′$_C$-H or 6′$_G$-H), 3.48 (1 H, dd, *J* 9.3 and 3.9, 2$_B$-H), 3.53 (1 H, dd, *J* 9.3 and 3.3, 2$_E$-H), 3.55 (1 H, br dd, *J* 10.2, 6′$_C$-H or 6′$_G$-H), 3.59 (1 H, br dd, *J* 9.6, 6′$_F$), 3.60 (1 H, br dd, *J* 10.2, 6′$_B$-H or 6′$_E$-H), 3.73 (1 H, dd, *J* 6.6 and 3.6, 2$_A$-H or 2$_D$-H), 3.74 (1 H, dd, *J* 6.6 and 3.6, 2$_A$-H or 2$_D$-H), 3.81 (1 H, dd, *J* 10.2 and 0.6, 6′$_B$-H or 6′$_E$-H), 3.88 (1 H, overlapped dd, 6$_C$-H or 6$_G$-H), 3.88 (1 H, br t, *J* 9.0, 4$_C$-H or 4$_G$-H), 3.89 (1 H, br t, *J* 9.0, 4$_C$-H or 4$_G$-H), 3.94 (1 H, dd, *J* 11.2 and 3.9, 6$_C$-H or 6$_G$-H), 4.00 (1 H, dd, *J* 9.0 and 8.4, 4$_F$-H), 4.03–4.25 (21 H, m, 5 × PhC*H*, 3$_A$-H, 3$_B$-H, 3$_C$-H, 3$_D$-H, 3$_E$-H, 3$_F$-H, 3$_G$-H, 4$_B$-H, 4$_E$-H, 5$_B$-H, 5$_C$-H, 5$_E$-H, 5$_F$-H, 5$_G$-H, 6$_B$-H or 6$_E$-H, 6$_F$-H), 4.25 (1 H, dd, *J* 11.4 and 3.6, 6$_B$-H or 6$_E$-H), 4.33 (2 H, AB, J_{AB} 12.3, Δν 12.7, PhCH_2), 4.38 (2 H, s, PhCH_2), 4.40–4.71 (21 H, m, 15 × PhC*H*, 4$_A$-H, 4$_D$-H, 5$_A$-H, 5$_D$-H, 6$_A$-H, 6$_D$-H), 4.78 (1 H, d, *J* 10.8, PhC*H*), 4.79 (1 H, d, *J* 11.4, PhC*H*), 4.80 (1 H, d, *J* 10.2, PhC*H*), 4.80 (1 H, d, *J* 11.4, PhC*H*), 4.83 (1 H, d, *J* 10.8, PhC*H*), 4.85 (1 H, d, *J* 10.2, PhC*H*), 4.86 (1 H, d, *J* 10.8, PhC*H*), 4.92 (1 H, dd, *J* 10.2 and 3.0, 6′$_A$-H or 6′$_D$-H), 4.94 (1 H, dd, *J* 10.8 and 3.0, 6′$_A$-H or 6′$_D$-H), 5.10 (1 H, d, *J* 10.8, PhC*H*), 5.12–5.19 (4 H, m, PhC*H*), 5.15 (1 H, d, *J* 3.0, 1$_F$-H), 5.17 (1 H, d, *J* 3.0, 1$_B$-H), 5.21 (1 H, d, *J* 11.4, PhC*H*), 5.23 (1 H, d, *J* 11.4, PhC*H*), 5.33 (1 H, d, *J* 3.6, 1$_E$-H), 5.37 (1 H, d, *J* 3.6, 1$_C$-H or 1$_G$-H), 5.39 (1 H, d, *J* 3.6, 1$_C$-H or 1$_G$-H), 5.47 (1 H, d, *J* 3.0, 1$_A$-H or 1$_D$-H), 5.48 (1 H, d, *J* 3.0, 1$_A$-H or 1$_D$-H), 6.98–7.38 (95 H, m, C_6H_5), 7.41 (1 H, d, *J* 8.4, 2″$_A$-H or 2″$_D$-H), 7.47 (1 H, d, *J* 8.4, 2″$_A$-H or 2″$_D$-H), 7.92 (1 H, d, *J* 9.0, 5″$_A$-H or 5″$_D$-H), 7.95 (1 H, d, *J* 9.0, 4″$_A$-H or 4″$_D$-H), 7.96 (1 H, t, *J* 7.8, 7″$_A$-H or 7″$_D$-H), 7.96 (1 H, d, *J* 9.0, 5″$_A$-H or 5″$_D$-H), 7.98 (1 H, t, *J* 7.8, 7″$_A$-H or 7″$_D$-H), 7.99 (1 H, d, *J* 9.0, 5″$_A$-H or 5″$_D$-H), 8.01 (1 H, d, *J* 8.4, 3″$_A$-H or 3″$_D$-H), 8.05 (1 H, d, *J* 9.0, 9″$_A$-H or 9″$_D$-H), 8.06 (1 H, d, *J* 8.4, 3″$_A$-H or 3″$_D$-H), 8.08 (1 H, d, *J* 9.0, 9″$_A$-H or 9″$_D$-H), 8.10 (1 H, d, *J* 7.8, 8″$_A$-H or 8″$_D$-H), 8.13 (1 H, dd, *J* 7.8 and 0.6, 8″$_A$-H or 8″$_D$-H), 8.15 (1 H, dd, *J* 7.8 and 0.6, 6″$_A$-H or 6″$_D$-H), 8.17 (1 H, dd, *J* 7.8 and 0.6, 6″$_A$-H or 6″$_D$-H), 8.54 (1 H, d, *J* 9.0, 10″$_A$-H or 10″$_D$-H), 8.56 (1 H, d, *J* 9.0, 10″$_A$-H or 10″$_D$-H); δ_C (151 MHz; d^6-acetone; Me_4Si) 69.69, 69.71 (2 C, 6$_{A,D}$-C), 70.22, 70.31 (2 C, 6$_{C,G}$-C), 70.41, 70.47 (2 C, 6$_{B,E}$-C), 70.54 (1 C, 6$_F$-C), 71.76, 71.85 (2 C, 5$_{A,D}$-C), 72.54, 72.68, 72.81, 72.88 (5 C, 5$_B$-, 5$_C$-, 5$_E$-, 5$_F$- and 5$_G$-C), 73.30,

73.32, 73.46, 73.84, 73.85, 73.96, 75.95, 76.01, 76.05, 76.19 (Ph*C*H), 78.74, 79.04 (2 C, $4_{B,E}$-C), 79.57 (1 C, 4_F-C), 79.78, 79.84, 79.96 (5 C, 2_C-, 2_G-, $4_{A/D}$-, 4_C- and 4_G-C), 80.14, 80.25, 80.30, 81.65 (6 C, 2_A-, 2_B-, 2_D-, 2_E-, 2_F- and $4_{A/D}$-C), 81.80, 81.95, 82.00, 82.05 (7 C, 3_{A-G}-C), 98.88, 99.06, 99.16, 99.36, 99.42 (7 C, 1_{A-G}-C), 110.86, 110.88 (2 C, $2''_{A,D}$-C), 121.22, 121.27 (2 C, $10a''_{A,D}$-C), 122.07, 122.12 (2 C, $10''_{A,D}$-C), 125.15, 125.19, 125.30, 125.34 (4 C, $6''_{A,D}$-C and $8''_{A,D}$-C), 125.67, 125.70 (2 C, $10c''_{A,D}$-C), 125.91, 125.96 (2 C, $5''_{A,D}$-C), 126.29, 126.33 (2 C, $3a''_{A,D}$-C), 126.54, 126.59, 126.66 (Ar-*C*H), 127.15, 127.19 (2 C, $7''_{A,D}$-C), 127.47 (2 C, $9''_{A,D}$-C), 127.70, 127.73, 127.80, 127.83, 128.05, 128.09, 128.13, 128.17, 128.19, 128.24, 128.30, 128.34, 128.39, 128.48, 128.46, 128.50, 128.55, 128.58, 128.60, 128.73, 128.74, 128.78, 128.80, 128.81, 128.88, 128.91, 128.93, 128.95, 128.97, 129.06, 129.08, 129.11 (Ar-*C*H), 132.53, 132.55, 132.66, 132.69 (4 C, $5a_{A,D}$-C and $8a_{A,D}$-C), 139.37, 139.48, 139.51, 139.55, 139.59, 139.60, 140.34, 140.38, 140.39, 140.41, 140.45 (Ar quaternary C), 153.78, 153.83 (2 C, $1_{A,D}$-C); *m*/*z* (MALDI/TOF): 3285.46 ($M + K^+$, 100%), 3269.48 ($M + Na^+$, 33%).

Fluorescence measurements

10^{-6} mol dm^{-3} solutions of **1** in water–DMSO mixtures of n : $(10 - n)$ v/v compositions were prepared by filling 10 mL volumetric flasks sequentially with 1 mL of a 10^{-5} mol dm^{-3} stock solution of **1** in DMSO, $(9 - n)$ mL of DMSO and n mL of water. The flasks were completed with the required amount of water–DMSO n : $(10 - n)$ v/v in order to compensate the default volume due to the non-ideal behavior of the solvent mixture. Acidic (0.04% HCl) 10^{-6} mol dm^{-3} solutions of **1** in water–DMSO 80 : 20 v/v containing various amounts of carboxylic acid substrates were prepared by filling 10 mL volumetric flasks sequentially with 1 mL of a 10^{-5} mol dm^{-3} stock solution of **1** in DMSO, $(1 - n)$ mL of a 0.5 mol dm^{-3} solution of guest in DMSO, n mL of DMSO, 0.08 mL of 5% aqueous HCl, and 7.92 mL of water. In the case of the alcohol substrates, the latter were replaced by 8 mL of water. The flasks were completed with the required amount of water–DMSO (80 : 20 v/v).

10 mm quartz cells were used throughout. Absorbances of the solutions were <0.1. Excitation wavelength was 355 nm. Excitation and emission slits were set to 1 nm. Spectra were collected on fresh solutions.

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