

# Quantum Dot/Cyclodextrin supramolecular systems based on efficient molecular recognition and their use for sensing

Jordi Aguilera-Sigalat, Juan M. Casas-Solvas, Maria C. Morant-Miñana, Antonio Vargas-Berenguel, Raquel E. Galian, and  
Julia Pérez-Prieto

## Electronic Supplementary Information

### TABLE OF CONTENTS

Title	page
<b>Experimental section</b>	S2
<b>Figure S1.</b> Preparation of CD-Py and CS@KP QDs	S6
<b>Figure S2.</b> A CS@KP/CD-Py supramolecular system	S7
<b>Figure S3.</b> Absorption spectrum of a deaerated acetonitrile/water (3/1) solution of <b>CD-Py</b> .	S7
<b>Table S1.</b> Photophysical properties of CS and CS@KP QDs in toluene.	S8
<b>Figure S4.</b> <sup>1</sup> H-NMR spectrum of CS2@KP in CDCl <sub>3</sub>	S9
<b>Figure S5.</b> Comparative absorbance spectra of deaerated acetonitrile/water (3/1) solutions of CS3@KP and CS3@KP/CD-Py system.	S10
<b>Table S2.</b> Fluorescence properties of CS and CS@KP QDs in ACN/H <sub>2</sub> O (3/1), both in the presence and in the absence of CD and CD-Py	S11
<b>Figure S6-</b> Comparative fluorescence spectra of deaerated acetonitrile/water (3/1) solutions of CS3@KP, CS3@KP/CD-Py and CS3@KP/CD	S12
<b>Figure S7-S8.</b> Transient absorption spectra of deaerated acetonitrile/water (3/1) solutions of <b>CD-Py</b> and <b>CS2@KP/CD-Py</b> 1.12, 2.72, and 8.8 μs after the laser pulse lamp (355 nm).	S13
<b>Figure S9.</b> Analysis of the response of the <b>CS2@KP/CD-Py</b> fluorescence to increasing amounts of indole in the presence and in the absence of analyte <b>1</b>	S14
<b>Figure S10.</b> <sup>1</sup> H-NMR in CDCl <sub>3</sub> of <b>7</b> , recovered in the toluene/acetonitrile organic phase after the molecular sensing assay.	S14
<b>References</b>	S15

## Experimental Section

**Materials.** All reagents were commercially available and used as received. The reagents were purchased from Sigma-Aldrich. Solvents were dried according to literature procedures.<sup>1</sup> Core-shell QDs capped with long-chain primary amine were purchased from Evident Technologies ([www.evidenttech.com](http://www.evidenttech.com)) and from Ocean NanoTech ([www.oceannanotech.com](http://www.oceannanotech.com)). Solvents for chromatography (ethyl acetate and hexane) were reagent grade and used without further purification. Distilled water (mili-Q) was used for the experiments.

**Characterization.** TLC was performed on Merck Silica Gel 60 F<sub>254</sub> aluminium sheets and developed by UV light and ethanolic sulfuric acid (5 % v/v). Flash column chromatography was performed on Merck Silica Gel (230-400 mesh, ASTM). Melting point was measured on a Büchi B-450 melting point apparatus and is uncorrected. Optical rotation was recorded on a Jasco P-1030 polarimeter at room temperature.  $[\alpha]_D$  value is given in  $10^{-1}$  deg cm<sup>2</sup> g<sup>-1</sup>. IR spectra were recorded on a Mattson Genesis II FTIR. <sup>1</sup>H, <sup>13</sup>C and 2D NMR spectra (gCOSY, gHMQC and gHMBC) were recorded on Bruker Avance DPX300 spectrometer equipped with a QNP <sup>1</sup>H/<sup>13</sup>C/<sup>19</sup>F/<sup>31</sup>P probe. Standard Bruker software was used for acquisition and processing routines. Chemical shifts are given in ppm and referenced to internal TMS ( $\delta_H$  and  $\delta_C$  0.00). *J* values are given in Hz. MALDI-TOF mass spectrum was recorded on an Applied Biosystems Voyager DR-RP spectrometer using  $\alpha$ -cyano-4-hydroxycinnamic acid as matrix.

UV-vis spectra of the samples were recorded using a quartz cuvettes in a UV-visible spectrophotometer Agilent 8453E. Steady-state fluorescence spectra were measured on a spectrofluorometer PTI, equipped with a lamp power supply (LPS-220B, motor driver (MD-5020), Brytebox PTI and working at room temperature. The average diameter value of the nanoparticles was estimated following the Peng *et al.*<sup>2</sup> procedure. The Felix 32 Analysis software was used to register the data. The excitation wavelength for the emission spectra was fixed at 450 nm for QD excitation and 343

nm for pyrene excitation. Laser flash photolysis (LFP) studies were performed on a pulsed Nd:YAG laser, using 355 nm as excitation source. The pulses width was ca. 10 ns, and the energy was ca. 15 mJ/pulse. A xenon lamp was employed as the detecting light source. The apparatus consisted of the pulsed laser, the Xe lamp, a monochromator, and a photomultiplier (PMT) system. The output signal from the oscilloscope was transferred to a personal computer. Samples of CS (3 mL) were prepared such that they absorbed ca. 0.3 at 355 nm and they were bubbled with N<sub>2</sub> for 10 min.

**2<sup>I</sup>-O-{3-[1-pyrenyl]-propyn-1-yl}cyclomaltoheptaose.** A solution of 1-bromopyrene<sup>3</sup> (65 mg, 0.235 mmol) and 2<sup>I</sup>-O-propargylcyclomaltoheptaose<sup>4</sup> (300 mg, 0.256 mmol) in dry piperidine (36 mL) was degassed by bubbling N<sub>2</sub> under sonication for 30 minutes. [Pd(PPh<sub>3</sub>)<sub>2</sub>Cl<sub>2</sub>] (27 mg, 0.024 mmol) was then added and the mixture was heated at 75 °C in the dark. After 30 minutes, CuI (4 mg, 0.024 mmol) was also added before the solution was stirred at that temperature for 17 h in the dark. The solvent was removed by evaporation under vacuum and the crude product was purified by column chromatography (CH<sub>3</sub>CN-H<sub>2</sub>O-(30 % v/v aq NH<sub>3</sub>) 8:2:1) to yield 2<sup>I</sup>-O-{3-[1-pyrenyl]-propyn-1-yl}cyclomaltoheptaose (170 mg, 0.122 mmol, 52 %) as a yellowish solid: mp 256 °C dec; [α]<sub>D</sub> +46 (c 0.25, H<sub>2</sub>O); IR (KBr): 3421, 2926, 1638, 1151, 1116, 1032, 618 cm<sup>-1</sup>; <sup>1</sup>H NMR (300 MHz; DMSO-*d*<sub>6</sub>, ppm) δ 8.61 (d, 1H, *J* = 9.2 Hz, Pyr), 8.38-8.12 (m, 8H, Pyr), 6.03-6.00 (m, 2H, OH), 5.81-5.70 (m, 11H, OH), 5.20 (d, 1H, <sup>3</sup>*J* = 3.0 Hz, H-1<sup>I</sup>), 4.99 (d, 1H, <sup>2</sup>*J* = 16.1 Hz, CHO), 4.91-4.84 (m, 7H, CHO, H<sup>II-VII</sup>), 4.75 (s, 1H, OH), 4.54-4.44 (m, 6H, OH), 3.92 (t, 1H, *J* = 9.5 Hz, H-3<sup>I</sup>), 3.71-3.51 (m, 29H, H-2<sup>I</sup>, 3<sup>II-VII</sup>, 4<sup>I</sup>, 6<sup>I-VII</sup>, 6<sup>I-VII</sup>), 3.42-3.27 (m, H-2<sup>II-VII</sup>, 4<sup>II-VII</sup>, overlapped with HDO); <sup>13</sup>C NMR (75 MHz; DMSO-*d*<sub>6</sub>, ppm) δ 131.3, 131.0, 130.7, 130.5, 129.7, 128.9, 128.5, 127.2, 126.8, 126.0, 125.0, 124.9, 123.5, 123.2, 116.2 (Pyr), 102.0-101.7 (C-1<sup>II-VII</sup>), 100.0 (C-1<sup>I</sup>), 91.5 (CH<sub>2</sub>C≡), 84.8 (≡C-Pyr), 82.3, 81.6-81.3 (C-4<sup>I-VII</sup>), 79.6 (C-2<sup>I</sup>), 73.3-71.8, 70.2 (C-2<sup>II-VII</sup>, 3<sup>I-VII</sup>, 5<sup>I-VII</sup>), 60.0-59.9 (C-6<sup>I-VII</sup>), 59.7 (CH<sub>2</sub>O); MALDI-TOF-MS *m/z* calcd for C<sub>61</sub>H<sub>80</sub>O<sub>35</sub> 1372.45, found 1395.03 (M + Na)<sup>+</sup>.

**Synthesis of CS.** Fluorescent CdSe nanocrystals were synthesized by Peng *et. al.*<sup>5</sup> procedure with some modifications. Briefly, a mixture of 2.3 mmol of CdO, 0.7 mmol of TDPA, and 9.1 mmol of TOPO was heated gradually up to 320 °C in a three-neck flask under N<sub>2</sub> flow. The reaction was maintained at this temperature for 10-15 min, until the solution was clear. Then, the reaction was cooled to 270 °C, and 1.2 mL of the SeTOP was quickly injected (SeTOP mixture was prepared by the addition of 0.3 mmol of Se and 3.4 mmol of TOP under N<sub>2</sub> flow at 70 °C). When the reaction turned orange the nanocrystals were precipitated in cool MeOH and purified several times by centrifugation with MeOH to remove the excess of starting materials. Finally, the QDs were re-dispersed in toluene.

The synthesis of core-shell CdSe/ZnS QDs (CS) was done following the Bawendi's procedure<sup>6</sup> with some modifications. For a typical reaction, 5 g of TOPO were heated up to 190°C in three-neck flask for 2 h under Ar flow. Then, the solution was cooled to 60 °C and 0.5 mL of TOP was added into the flask. After that, 2 mL of QD was added and the reaction was heated to 140 °C. Then, the shell was added drop-wise for 10 min. For the shell, 440 µL of ZnEt<sub>2</sub>, 65 µL of (TMS)<sub>2</sub>S, and 2600 µL of TOP were mixed in a glove box under N<sub>2</sub> flow. Then, the reaction was cooled to 90 °C and kept at this temperature for 3 h. For the purification, the CdSe/ZnS QDs were precipitated in MeOH several times. Finally, CS was redissolved in toluene.

**Synthesis of 11-mercaptoundecyl-2-(3-benzoylphenyl)propanoate (KP-SH).** The KP-SH ligand was prepared following an esterification method described in the literature. In brief, ketoprofen (500 mg, 2.0 mmol) and 11-mercapto-1-undecanol (402 mg, 2.0 mmol) were dissolved in anhydride toluene (24 mL). A complex of hafnium/THF (1.8 mg) was added and the mixture was heated for 48 h under azeotropic reflux conditions to remove water through a Soxhlet thimble with 3 Å molecular sieves. In order to quench the reaction, 1 mL of water was added. The product was purified by column

chromatography performed on silica gel 60 (230-400 mesh) using a 10:1 mixture of hexane:ethyl acetate. The compound was obtained in a 81% yield.  $^1\text{H}$  NMR (300 MHz,  $\text{CDCl}_3$ ): d 1.00-1.34 (m, 14H), 1.25 (t,  $J= 7.7$  Hz; 1H), 1.45-1.57 (m, 7H), 2.43 (q,  $J= 7.1$  Hz; 2H), 3.73 (q,  $J= 7.2$  Hz; 1H), 3.99 (t,  $J= 6.7$  Hz; 2H), 7.33-7.55 (m, 5H), 7.60 (dt,  $J= 6.2$  Hz,  $J= 1.5$  Hz; 1H), 7.67-7.75 (m, 3H) ppm.

**Ligand exchange of the CS ligand by thiol.** For the exchange ligand procedure, 1 mL of CS and 143 mg of KP-SH (molar ratio between CS/ligand is 1/5000) were added in a flask and heated up to reflux in 40 mL of chloroform for 48 h, under  $\text{N}_2$  flow in absence of light. Then, the reaction was cooled down to room temperature. For the purification, the nanocrystals were precipitated in MeOH several times. Finally, the CS@KP obtained was dissolved in toluene.

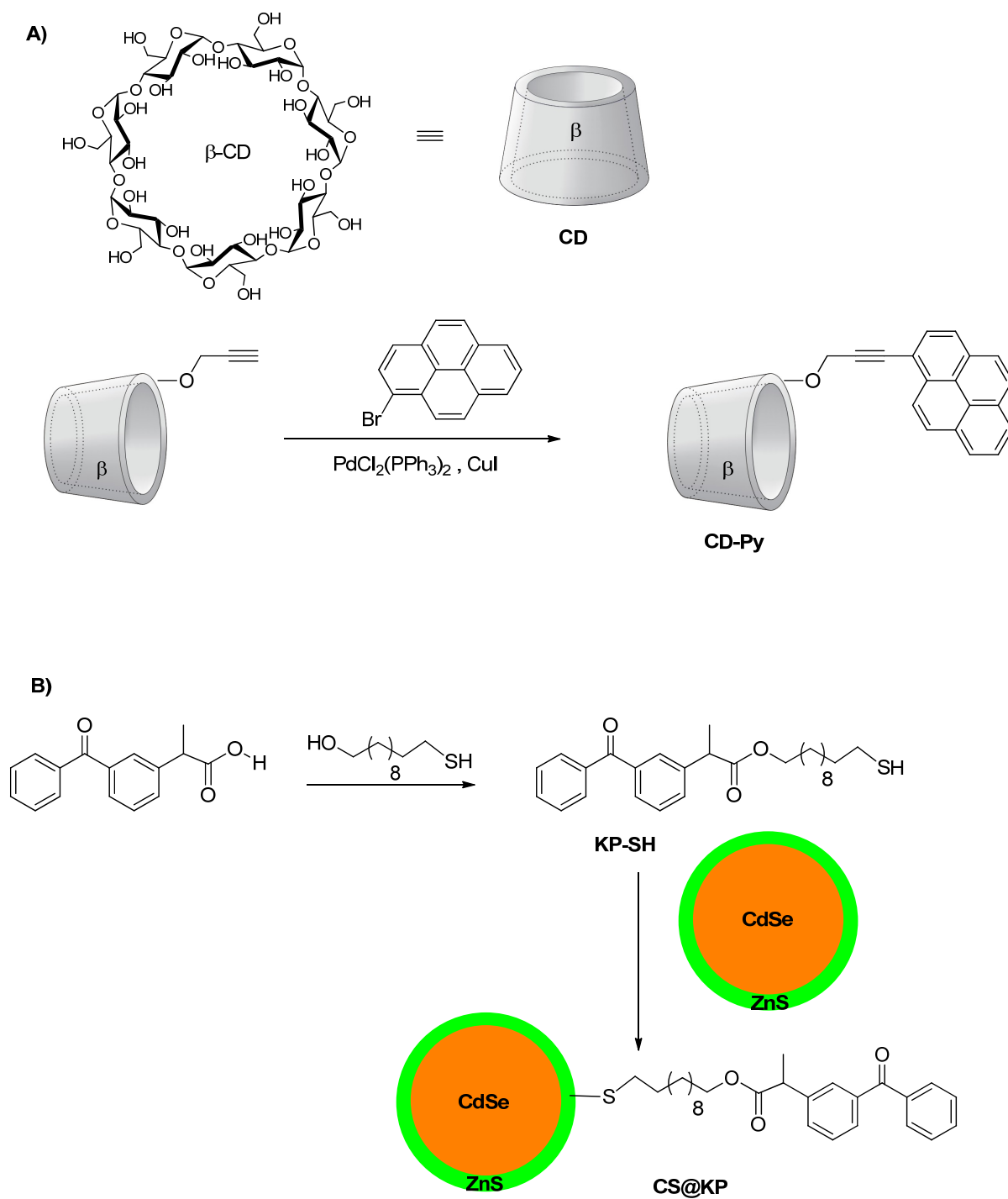
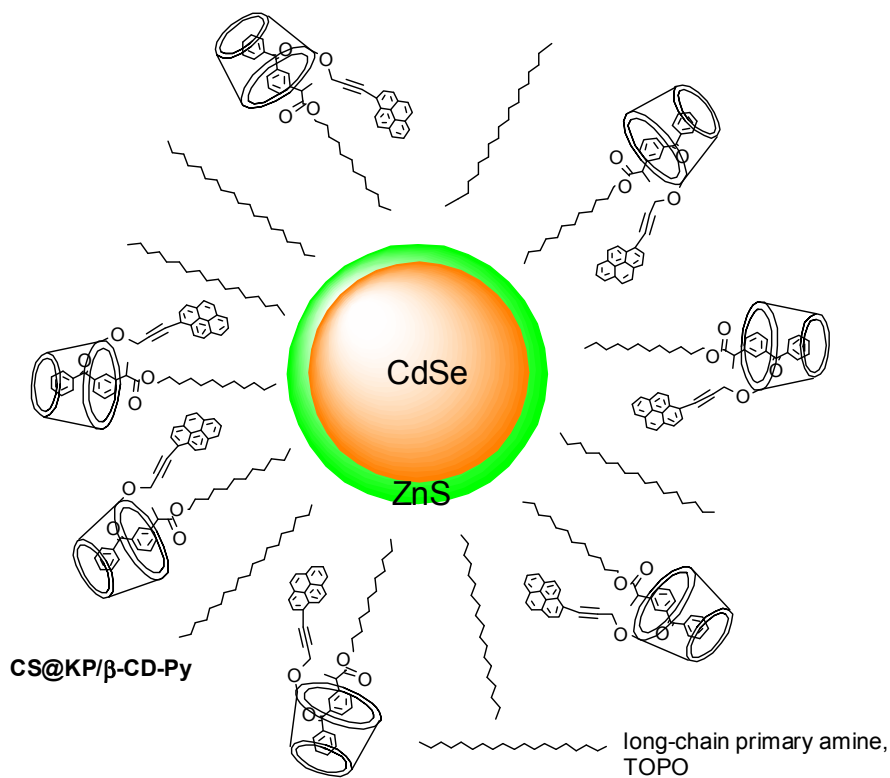
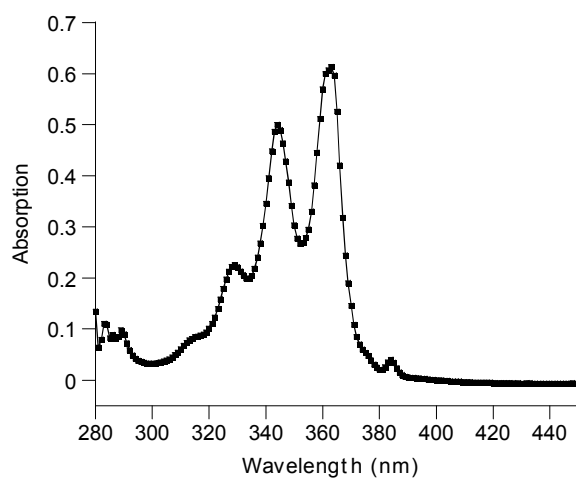


Fig. S1. Preparation of CD-Py and CS@KP QDs



**Fig. S2.** A CS@KP/CD-Py supramolecular system



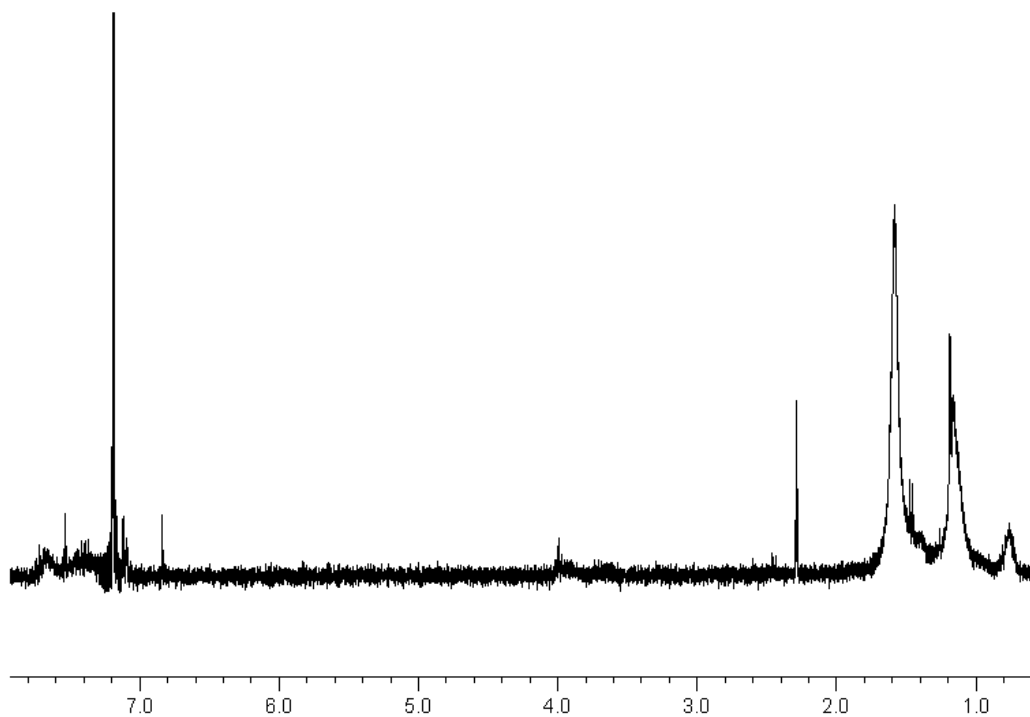
**Fig. S3.** Absorption spectrum of a deaerated acetonitrile/water (3/1) solution of CD-Py ( $5 \times 10^{-5}$  M).

**Table S1.** Photophysical properties of CS and CS@KP QDs in toluene.

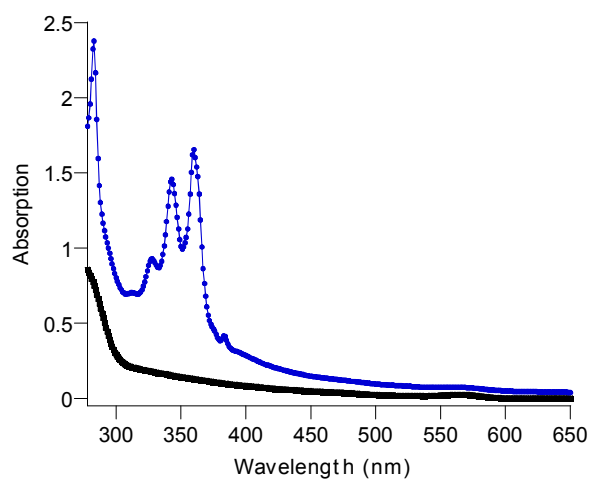
	$\lambda_{\text{abs}}$ (nm)	$\lambda_{\text{em}}$ (nm)	$\phi_f^a$	D (nm)
CS1	521	539	0.61	2.65
CS1@KP	519	541	0.56	2.55
CS2	544	562	0.55	2.93
CS2@KP	543	561	0.51	2.92
CS3	555	571	0.25	3.14
CS3@KP	553	572	0.10	3.10
CS4	541	549	0.34	2.87
CS4@KP	541	550	0.13	2.87

<sup>a</sup>Quantum dot fluorescence quantum yield was calculated by comparing the integrated emission spectra of the QD and fluorescein ( $\phi_f = 0.87$ , NaOH 0.1 M,  $\lambda_{\text{exc}} = 465$  nm) according to the procedure described by Resch-Genger *et al.*<sup>7</sup>





**Fig. S4.** <sup>1</sup>H-NMR spectrum of CS<sub>2</sub>@KP in CDCl<sub>3</sub>.

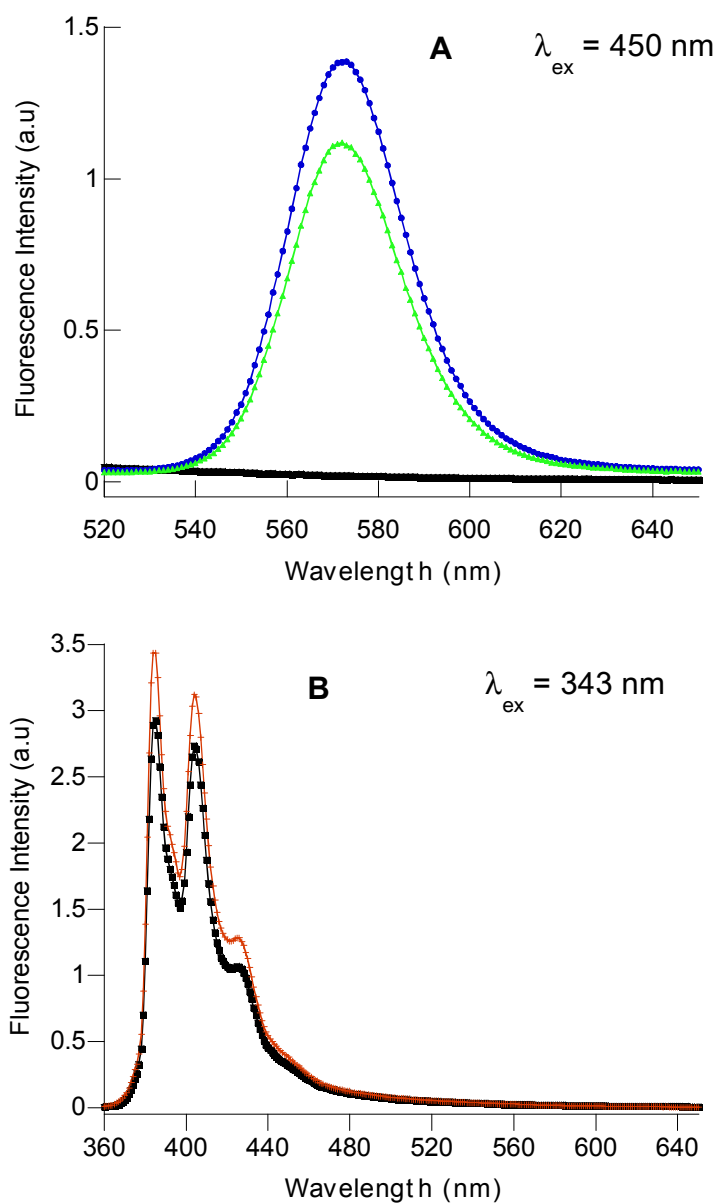


**Fig. S5.** Comparative absorbance spectra of deaerated acetonitrile/water (3/1) solutions of **CS3@KP** ( $4 \times 10^{-7}$  M, ■) and **CS3@KP/CD-Py** system ( $[CS] = 4 \times 10^{-7}$  M, ratio CS/CD = 1/1000, ●)

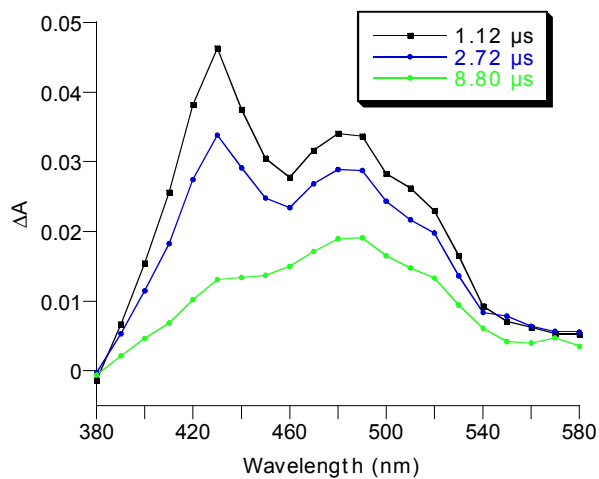
**Table S2.** Fluorescence properties (quantum yield,  $\Phi_f$ , and maximum of the emission peak,  $\lambda_{em}$ , of the emission) of CS and CS@KP QDs in ACN/H<sub>2</sub>O (3/1), both in the presence and in the absence of CD and CD-Py.

System	(CD/QD molar ratio)	$\Phi_f^a$			$\lambda_{em}^b$ (nm)		
		-	CD-Py	CD	- <sup>c</sup>	CD-Py	CD
CS1@KP		0.56			549		
	(1000/1)		0.05	0.64		544	548
CS2@KP		0.51			569		
	(1000/1)		0.11	0.53		564	569
CS3@KP		0.10			572		
	(1000/1)		<0.01	0.12		-	572
CS4@KP		0.13			550		
	(1000/1)		<0.01	0.11		-	550
	(3000/1)		<0.01	0.12		-	550
CS2		0.58			551		
	(1000/1)		0.53	0.60		553	-
CS3		0.34					
	(1000/1)		0.31	-	552	551	551

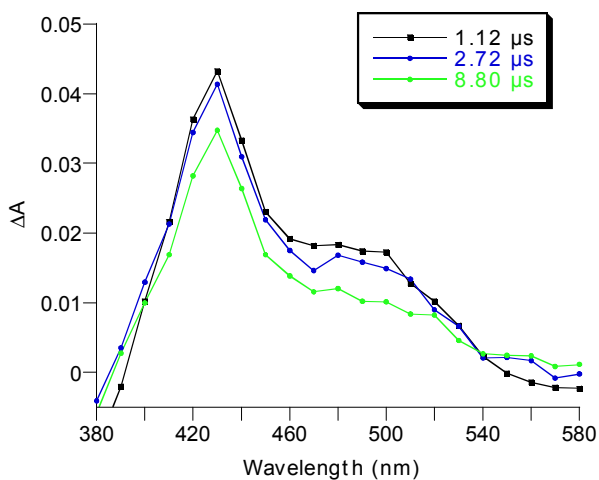
[CS1@KP] =  $3.85 \times 10^{-7}$  M; [CS2@KP] =  $3.1 \times 10^{-8}$  M; [CS3@KP] =  $5.2 \times 10^{-7}$  M; [CS4@KP] =  $1.8 \times 10^{-7}$  M; [CS2] =  $4.8 \times 10^{-8}$  M; [CS3] =  $6.3 \times 10^{-8}$  M. <sup>a</sup>The fluorescence quantum yield was calculated by following the procedure of Resch-Genger *et al.* (ref. 4 of Supporting Information). <sup>b</sup>Maximum of fluorescence intensity was calculated at  $\lambda_{ex} = 450$  nm. <sup>c</sup>The observed red-shift of the fluorescence maximum of the CS was expected due to a change in the solvent dielectric constant.<sup>8</sup>



**Fig. S6. A:** Comparative fluorescence spectra ( $\lambda_{ex} = 450 \text{ nm}$ ) of deaerated acetonitrile/water (3/1) solutions of **CS3@KP** ( $4 \times 10^{-7} \text{ M}$ ,  $\blacktriangle$ ), **CS3@KP/CD-Py** ( $[\text{QD}] = 4 \times 10^{-7} \text{ M}$ ,  $[\text{CD}] = 4 \times 10^{-4} \text{ M}$ ,  $\blacksquare$ ), and **CS3@KP/CD** ( $[\text{QD}] = 4 \times 10^{-7} \text{ M}$ ,  $[\text{CD}] = 4 \times 10^{-4} \text{ M}$ ,  $\bullet$ ). **B:** Comparative fluorescence spectra of deaerated acetonitrile/water (3/1) solutions of **CS3@KP/CD-Py** ( $[\text{QD}] = 4 \times 10^{-7} \text{ M}$ ,  $[\text{CD}] = 4 \times 10^{-4} \text{ M}$ ,  $\blacksquare$ ) and **CD-Py** ( $4 \times 10^{-4} \text{ M}$ ,  $+$ ) at  $\lambda_{ex} = 343 \text{ nm}$ .

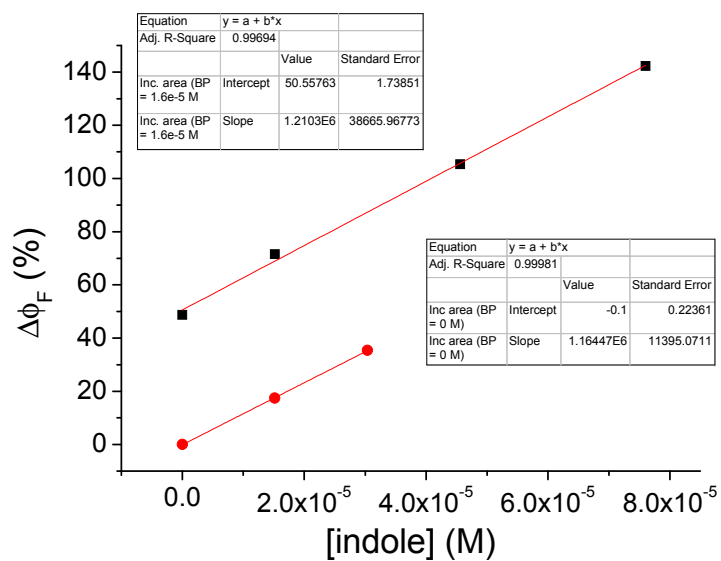


**Fig. S7.** Transient absorption spectra of a deaerated acetonitrile/water (3/1) solution of **CD-Py** ( $1.11 \times 10^{-4}$  M) 1.12, 2.72, and 8.8  $\mu$ s after the laser pulse lamp (355 nm).

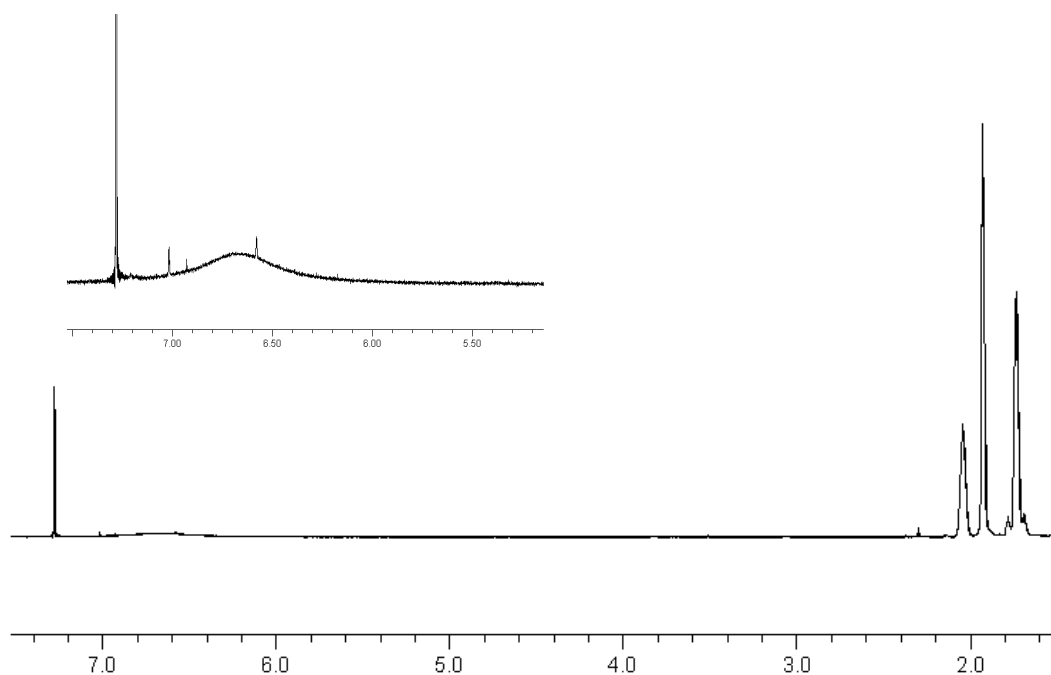


**Fig. S8.** Transient absorption spectra of a deaerated acetonitrile/water (3/1) solution of **CS2@KP/CD-Py** ([CS] =  $1.11 \times 10^{-7}$  M, [CD-Py] =  $1.11 \times 10^{-4}$  M) 1.12, 2.72, and 8.8  $\mu$ s after the laser pulse lamp (355 nm).

assay.



**Fig. S9.** Analysis of the response of the **CS2@KP/CD-Py** fluorescence to increasing amounts of indole in the presence (■) and in the absence (●) of analyte 1.



**Fig. S10.**  $^1\text{H-NMR}$  in  $\text{CDCl}_3$  of **7**, recovered in the toluene/acetonitrile organic phase after the molecular sensing

## REFERENCES

- 
- <sup>1</sup> Perrin, D. D.; Armarego, W. F. L. *Purification of Laboratory Chemicals*, 3rd ed.; Pergamon Press: Oxford, **1989**.
- <sup>2</sup> Yu, W. W.; Qu, L.; Guo, W.; Peng, X. *Chem. Mater.* **2003**, *15*, 2854-2860
- <sup>3</sup> Gumprecht, W. H. *Organic Syntheses*, **1968**, *48*, 30-31.
- <sup>4</sup> Casas-Solvas, J. M.; Ortiz-Salmerón, E.; Fernández, I.; García-Fuentes, L.; Santoyo-González, F.; Vargas-Berenguel, A. *Chem.-Eur. J.* **2009**, *15*, 8146-8162.
- <sup>5</sup> Peng, Z. A.; Peng, X. *J. Am. Chem. Soc.* **2001**, *123*, 183-184
- <sup>6</sup> Dabbousi, B. O.; Rodriguez-Viejo, J.; Mikulec, F. V.; Heine, J. R.; Mattoussi, H.; Ober, R.; Jensen, K. F. and Bawendi, M. G.; *J. Phys. Chem. B*, **1997**, *101*, 9463
- <sup>7</sup> Grabolle, M.; Spieles, M.; Lesnyak, V.; Gaponik, N.; Eychmüller, A. and Resch-Genger, U.; *Anal. Chem.* **2009**, *81*, 6285-6294
- <sup>8</sup> Leatherdale, C. A.; Bawendi, M. G. *Phys. Rev. B: Condens. Matter Mater. Phys.* **2001**, *63*, 165315.