Supplementary Material (ESI) for Chemical Communications

Selective Sulfate Binding Induces Helical Folding of an Indolocarbazole Oligomer in Solution and Solid State

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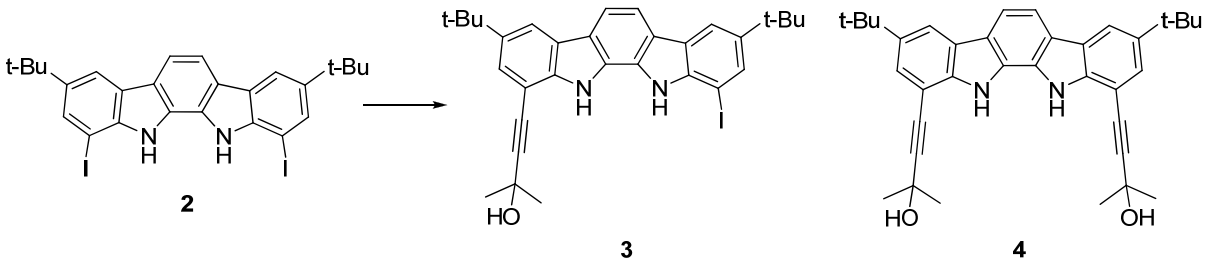
Contents

General: Air- or moisture-sensitive reactions were carried out under nitrogen. Reagents and solvents obtained from commercial suppliers were used without further purification, otherwise noted. Triethylamine was distilled over CaH_2 and THF was distilled from sodium-benzophenone. Thin layer chromatography (TLC) was performed on Merck (silica gel 60, F-254, 0.25 mm). Silica gel 60 (230 - 240 mesh, Merck) was used for column chromatography. NMR spectra were recorded by using Bruker DRX 400 instruments, the chemical shifts were reported in ppm downfield relative to the residual protonated solvent peaks (for ^{1}H NMR spectra, ($CDCl_3$ 7.26 ppm; CD_3CN 1.94 ppm; DMSO-d_6 2.50 ppm), and (for ^{13}C NMR spectra, $CDCl_3$ 77.16 ppm; DMSO-d_6 39.52 ppm; CD_2Cl_2 54.00 ppm). Melting points were measured by using a Barnstead Electrothermal (IA9100) apparatus and are uncorrected. The UV/Vis spectra were recorded by using an Agilent 8453 UV-visible spectrophotometer, fluorescence spectra by using F-4500 fluorescence spectrophotometer, and FTIR spectra by using a Nicolet Impact-400 FTIR spectrometer. The elemental analysis data were obtained from *the National Center for Inter-University Research Facilities* at the Seoul National University.

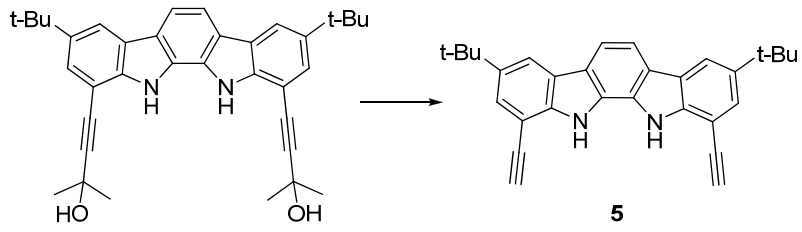
1. Synthesis of 1



Synthesis of **3**, **4**: A dry schlenk flask containing **2**[1] (3.00 g, 4.84 mmol), $Pd(PPh_3)_2Cl_2$ (0.017 g, 0.007 equiv) and CuI (0.005 g, 0.007 equiv) was evacuated under vacuum and back-filled with nitrogen three times. Degassed THF (9 mL), Et_3N (8 mL) and 2-methyl-3-butyn-2-ol (0.33 mL, 1 equiv) were sequentially added and the solution was stirred at 55-60 □ for 24 h. The mixture was filtered through celite and the organic solution was concentrated. The residue was dissolved in ethyl acetate and the organic solution was washed with saturated $NaHCO_3$ solution and brine, dried over

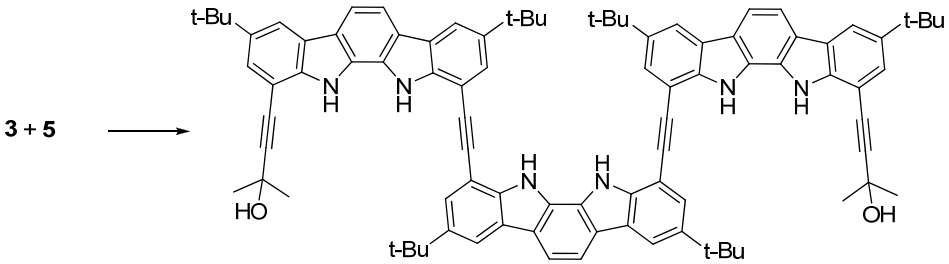
[1] (a) K.-J. Chang, D. Moon, M. S. Lah and K.-S. Jeong, *Angew. Chem. Int. Ed.,* 2005, **44**, 7926-7929; *Angew. Chem*. **2005**, *117*, 8140 – 8143; (b) N.-K. Kim, K.-J. Chang, D. Moon, M. S. Lah and K.-S. Jeong, *Chem. Commun.,* 2007, 3401-3403.

anhydrous $MgSO_4$ and concentrated. The residue was purified by column chromatography (silica gel, EtOAc/hexane = 1/3, v/v) to give **3** as a white solid (0.99 g, 51%) and **4** as a white solid (0.26 g, 23%). **3**: mp 295-296 □; IR (thin film): $\tilde{\nu}$= 3395 (OH and NH overlapped), 2215 (C≡C), 1153 cm^{-1} (C-O); ^1H NMR (400MHz, DMSO-d_6): δ = 9.25 (s, 1H, NH), 8.73 (s, 1H, NH), 8.08 (s, 1H, ArH), 8.05 (s, 1H, ArH), 7.92 (d, *J* = 8.3 Hz, 1H, ArH), 7.86 (d, *J* = 8.3 Hz, 1H, ArH), 7.79 (s, 1H, ArH), 7.54 (s, 1H, ArH), 2.82 (s, 1H, OH), 1.82 (s, 6H, Me), 1.45 (s, 9H, t-Bu), 1.43 ppm (1H, 9H, t-Bu); ^{13}C NMR (100 MHz, DMSO-d_6): δ = 143.9, 141.8, 139.1, 137.2, 130.7, 125.7, 125.5, 123.9, 123.7, 121.0, 120.6, 116.9, 116.2, 112.4, 112.3, 104.9, 99.7, 77.6, 76.7, 64.1, 34.4, 34.4, 31.9, 31.75, 31.74 ppm; elemental analysis calcd (%) $C_{31}H_{33}IN_2O$: C 64.58, H 5.77, I 22.01, N 4.86. **4**: mp 319-320 □; IR (thin film): $\tilde{\nu}$ = 3354 (OH and NH overlapped), 2214 (C≡C), 1160 cm^{-1}(C-O); ^1H NMR (400MHz, DMSO-d_6): δ = 11.00 (s, 2H, NH), 8.22 (s, 2H, ArH), 7.99 (s, 2H, ArH), 7.47 (s, 2H, ArH), 5.67 (s, 2H, OH), 1.99 (s, 12 H, Me), 1.42 ppm (s, 18H, t-Bu); ^{13}C NMR (100 MHz, DMSO-d_6): δ = 142.5, 138.7, 125.9, 124.9, 124.0, 121.6, 117.3, 104.4, 97.4, 80.1, 77.0, 67.1, 34.8, 32.0 ppm; elemental analysis calcd (%) $C_{36}H_{40}N_2O_2$: C 81.17, H 7.57, N 5.26, O 6.01; found C 81.15, H 7.66, N 5.31.



4 **5**

Synthesis of **5**: **4** (0.26 g) was dissolved in toluene (10 mL) containing KOH (0.06 g). The solution was stirred for 3 h at 90-94 □ temperature and filtered to remove insoluble salts. After concentration, the residue was purified by column chromatography (silica gel, CH_2Cl_2/hexane = 1/3, v/v) to give **5** as a white solid (0.11 g, 54%). mp 265-266 □; IR (thin film): $\tilde{\nu}$ = 3367 (NH), 2158 (C≡C), 3253 cm^{-1} (C(sp)-H); ^1H NMR (400 MHz, $CDCl_3$): δ = 8.41 (s, 2H, NH), 7.53 (s, 2H, ArH), 7.35 (s, 2H, ArH), 7.27 (s, 2H, ArH), 4.54 (s, 2H, C≡CH), 1.24 ppm (s, 18H, *t*-Bu); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 137.5, 126.3, 125.1, 123.4, 119.8, 113.1, 110.1, 83.5, 79.3, 33.7, 30.8, 25.3, 23.1 ppm; elemental analysis calcd (%) for $C_{30}H_{28}N_2$: C 86.50, H 6.78, N 6.73; found C 86.48, H 6.78, N 6.73.



1

Synthesis of **1**: A Schlenk flask containing **3** (0.456 g, 0.791 mmol, 2.1 equiv), $Pd(PPh_3)_2Cl_2$ (0.013 g, 0.05 equiv) and CuI (0.004 g, 0.05 equiv) was evacuated under vacuum and back-filled with nitrogen three times. Degassed THF (4 mL), Et_3N (4 mL) and **5** (0.156 g, 1 equiv) were sequentially added, and the solution was stirred at 52-55 □ for 24 h. The mixture was filtered through celite and the organic solution was concentrated. The residue was dissolved in ethyl acetate and the organic solution was washed with saturated $NaHCO_3$ solution and brine, dried over anhydrous $MgSO_4$ and concentrated. The residue was purified by column chromatography (silica gel, EtOAc/hexane = 1/4, v/v) to give **1** as a white solid (0.310 g, 63%). mp > 300 □ (dec); IR (thin film): $\tilde{\nu}$ = 3399 (OH and NH overlapped), 2209 (C≡C), 1159 cm^{-1} (C-O); ^{1}H NMR (400 MHz, DMSO-d_6): δ = 11.35 (s, 2H, NH), 11.25 (s, 2H, NH), 10.79 (s, 2H, NH), 8.39 (s, 2H, ArH), 8.26 (s, 2H, ArH), 8.20 (s, 2H, ArH), 8.11 (s, 2H, ArH), 8.01 (s, 4H, ArH), 7.85 (s, 2H, ArH), 7.68 (s, 2H, ArH), 7.43 (s, 2H, ArH), 5.50 (s, 2H, OH), 1.54 (s, 12H, Me), 1.52 (s, 18H, *t*-Bu), 1.40 (s, 18H, *t*-Bu), 1.29 ppm (s, 18H, *t*-Bu); ^{13}C NMR (100 MHz, CD_2Cl_2, taken in the presence of tetrabutylammonium chloride (1 equiv)): δ = 142.9, 142.3, 141.2, 138.7, 138.2, 137.9, 127.5, 127.3, 127.2, 126.4, 125.9, 125.2, 124.9, 124.0, 121.8, 121.6, 121.0, 117.4, 117.1, 116.7, 112.2, 111.6, 111.4, 106.0, 104.7, 97.2, 92.8, 91.8, 78.6, 65.6, 58.3, 35.3, 35.0, 32.7, 32.5, 32.4, 31.8, 30.3, 23.7, 19.7, 13.6 ppm; HRMS-FAB (*m/z*) calcd. for $C_{92}H_{92}N_6O_2$ 1312.7282, found 1313.7282; elemental analysis calcd (%) for $C_{92}H_{92}N_6O_2$: C 84.11, H 7.06, N 6.40; found C 84.21, H 7.09, N 6.33.

2. 1D and 2D NMR spectra

1) ^{1}H NMR spectra of **1** in the present of an anion.

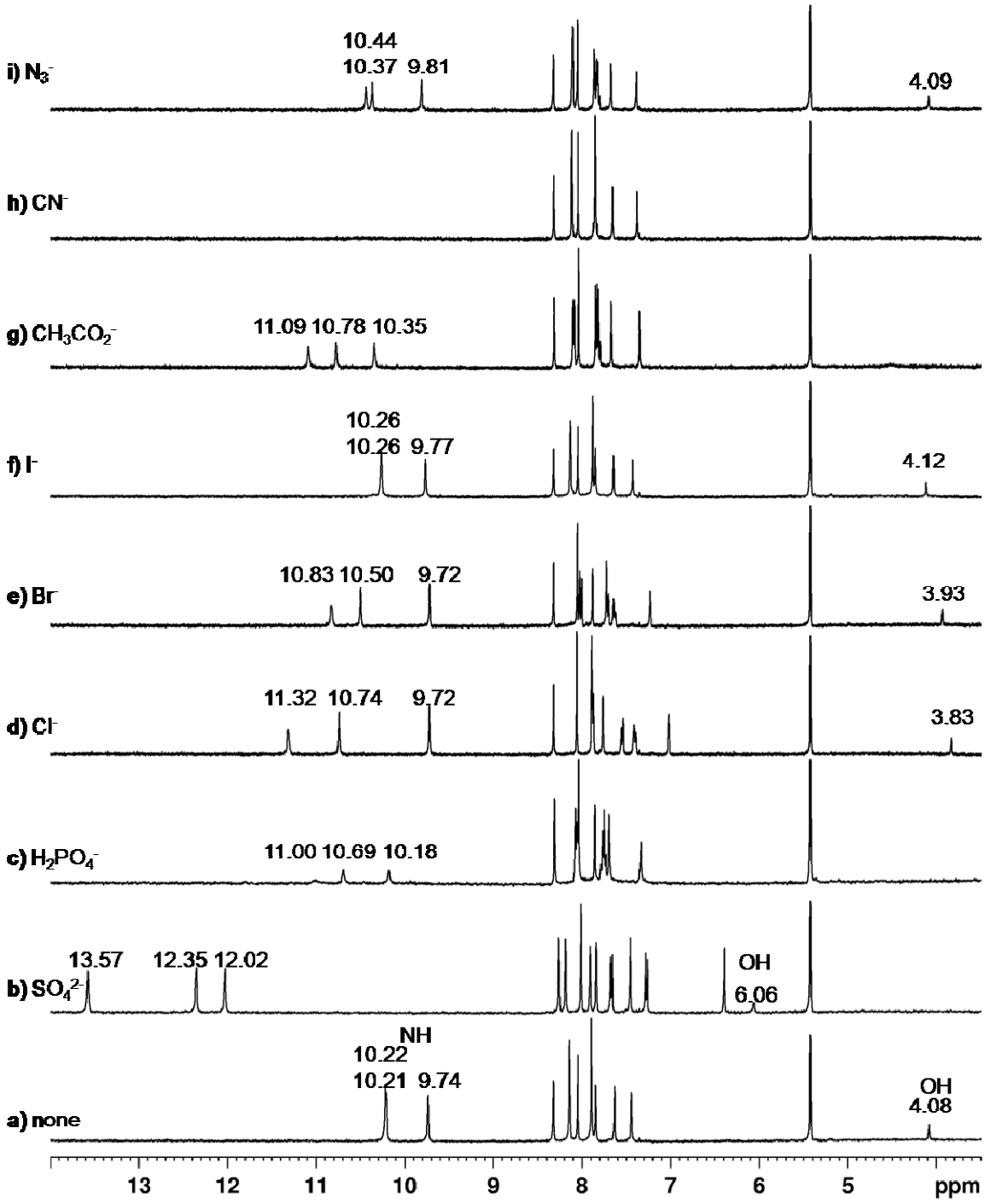


Figure S1. Partial ^{1}H NMR spectra (400 MHz, 1:1:8 (v/v) $CD_2Cl_2/CD_3OH/CD_3CN$, 298 K) of **1** in the presence of anions: (a) **1** free (0.5×10^{-3} M), (b)-(i) in the presence of each anion (1 equiv). Anions are used as tetrabutylammonium salts (bottom to top): none, SO_4^{2-}, $H_2PO_4^-$, Cl^-, Br^-, I^-, $CH_3CO_2^-$, CN^-, and N_3^-.

Table S1. Upon addition of an anion (1 equiv) chemical shift changes ($\Delta\delta=\delta_{obsd}-\delta_{free}$) of NH and OH signals.

Anion	Δδ(NHs) (ppm)	Δδ(OH) (ppm)
SO_4^{2-}	2.28, 2.14, 3.35	1.98
$H_2PO_4^-$	0.44, 0.48, 0.78	[a]
Cl^-	-0.02, 0.53, 1.10	-0.25
Br^-	-0.02, 0.29, 0.61	-0.15
I^-	0.03, 0.05, 0.06	0.04
$CH_3CO_2^-$	0.61, 0.57, 0.87	[a]
CN^-	[a]	[a]
N_3^-	0.07, 0.16, 0.22	0.01

[a] disappeared

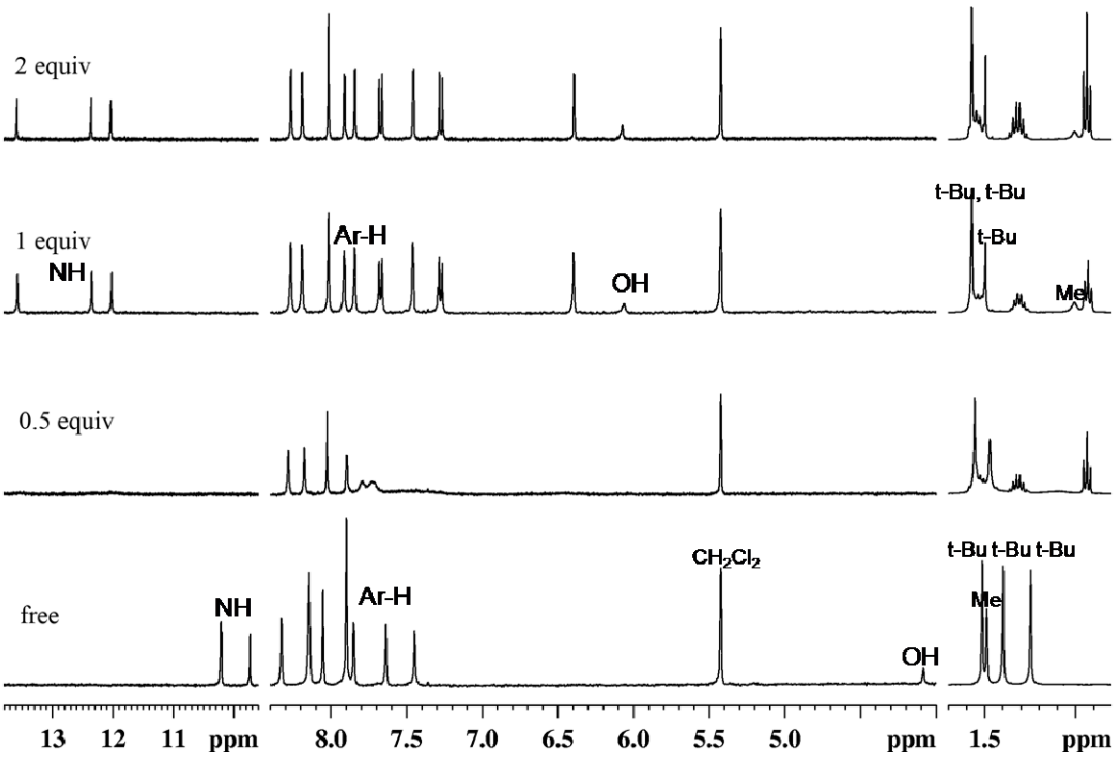


Figure S2. ^{1}H NMR spectral changes of **1** upon addition of tetrabutylammonium sulfate.

2) 2D ^{1}H-^{1}H NMR (TOCSY, NOESY) experiments.

The TOCSY and NOESY experiments were carried out at 25℃ using the pulse programs of mlevph and noesyph, respectively, and the mixing times were 80 ms (TOCSY) and 650 ms (NOESY). The sample was prepared by dissolving **1** (3×10^{-3} M) and tetrabutylammonium sulfate (2 equiv) in 1:1:8 (v/v) $CD_2Cl_2/CD_3OH/CD_3CN$.

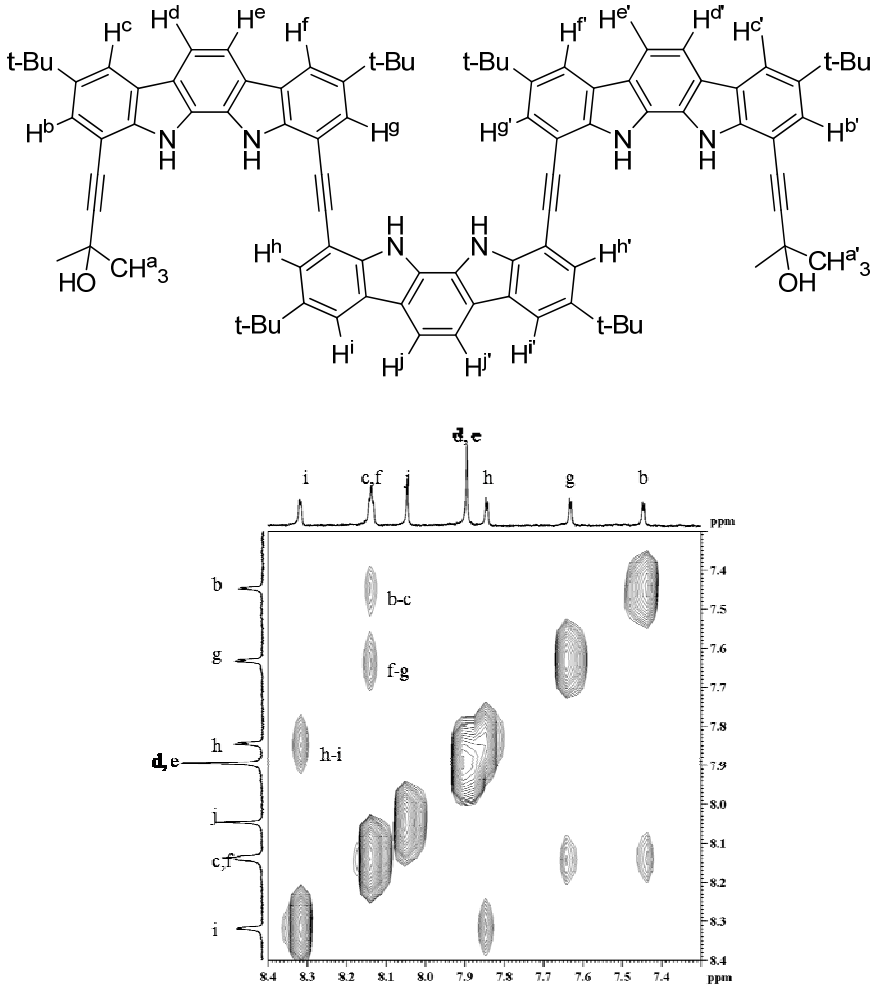


Figure S3. TOCSY spectrum (400 MHz, 25℃) of **1.**

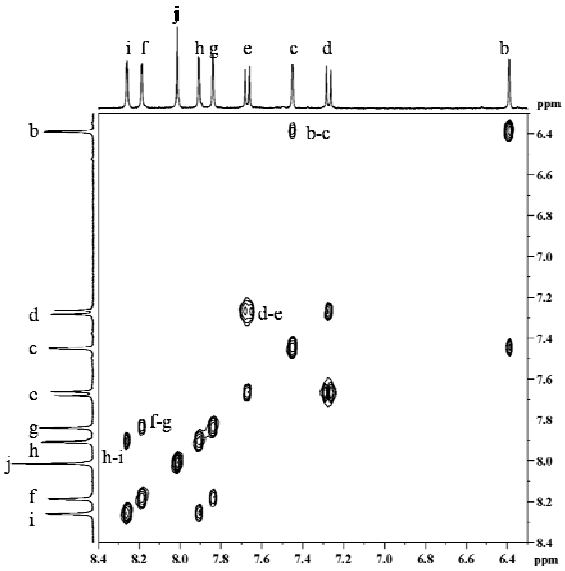


Figure S4. TOCSY spectrum (400 MHz, 25℃) of **1**·$(Bu_4N^+)_2SO_4^{2-}$.

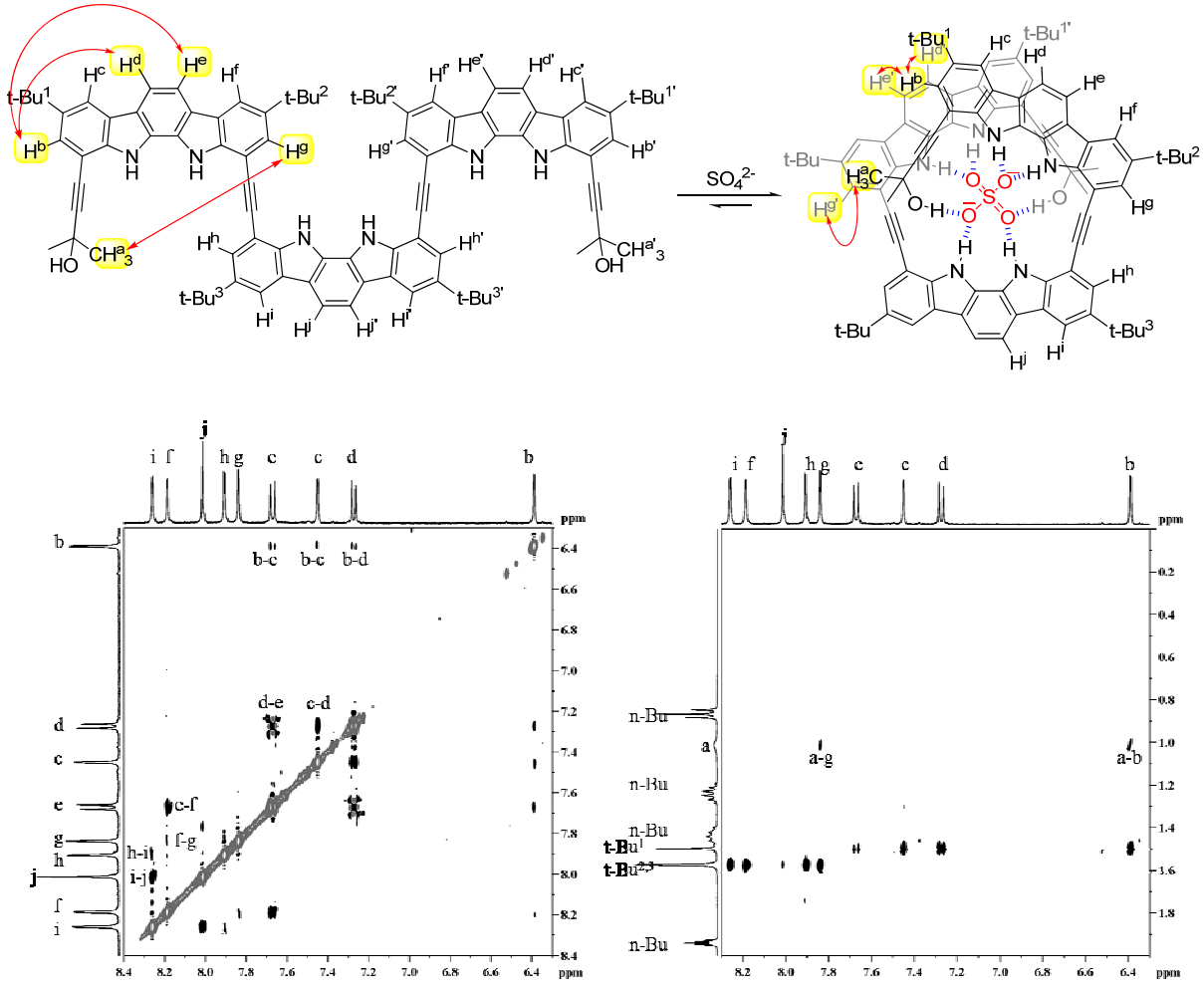


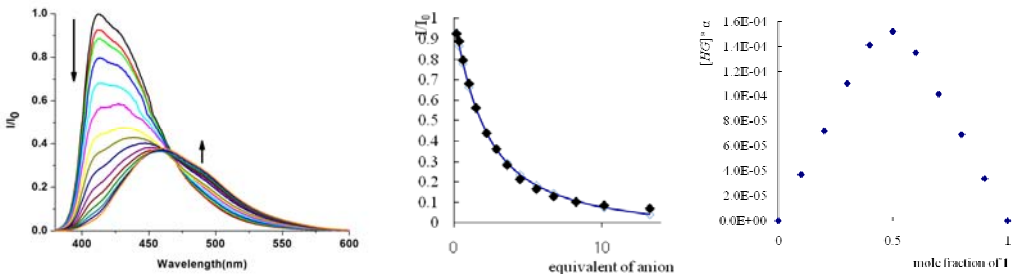
Figure S5. NOESY spectrum (400 MHz, 25℃) of **1**·$(Bu_4N^+)_2SO_4^{2-}$.

3. Binding Studies

1) Titrations: Titration experiments were carried out with F-4500 fluorescence spectrophotometer, and CH_3OH and CH_3CN of a spectroscopic grade were degassed prior to use. A stock solution of **1** (1.0×10^{-6} M) in 10% (v/v) CH_3OH/CH_3CN (25 mL) was first prepared for the fluorescence titration. Using this solution as a solvent, a stock solution of an anion (1.8×10^{-6} - 8.0×10^{-2} M) was prepared. Small portions of the anion solution were added to the solution of **1** (1.0 mL), and the spectrum was recorded after each addition, thus affording overall 12-15 data points at 25 ± 1 □. The association constants (K_a) were determined by nonlinear curve fitting of the titration curves[2], plotting emission at 413 nm against equivalents of the anion added. All of the titration curves were well fitted to the expression of a 1:1 binding isotherm.

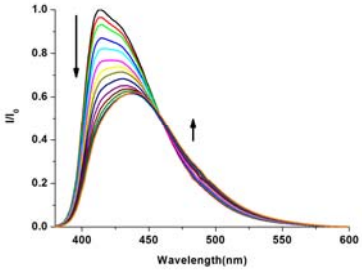
2) Job's plots[3]: Stock solutions of **1** (4.0×10^{-5} M) and an anion (4.0×10^{-5} M) were separately prepared in 10% (v/v) CH_3OH/CH_3CN. The UV/Vis spectrum was taken for each of 10 different solutions containing total 2.0 mL of the macrocycle and an anion in the following ratios: 1:0, 0.9:0.1, 0.8:0.2, 0.7:0.3, 0.6:0.4, 0.5:0.5, 0.4:0.6, 0.3:0.7, 0.2:0.8, 0.1:0.9. Job's plots were constructed by plotting $[HG]\cdot\alpha$ against mol fraction of **1**.

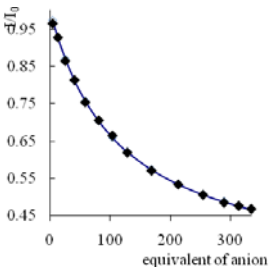
i) **1** + $(Bu_4N^+)_2SO_4^{2-}$

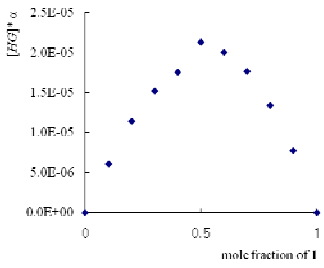


[2] J. R. Long, R. S. Drago, *J. Chem. Edu*. **1982**, *59*, 1037-1089.
[3] K. A. Connors, *Binding Constants*; John Wiley & Sons: New York, **1987**.

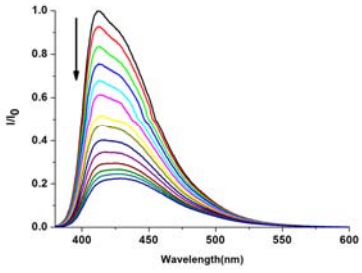
ii) **1** + $Bu_4N^+Cl^-$

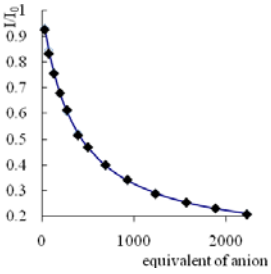


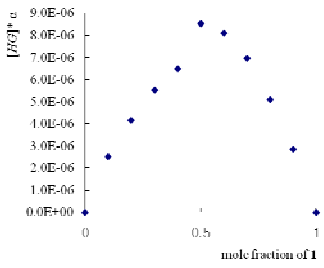




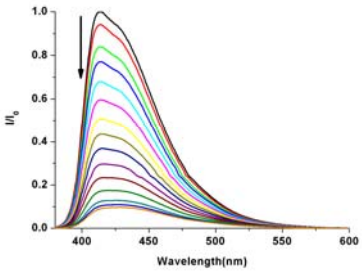
iii) **1** + $Bu_4N^+Br^-$

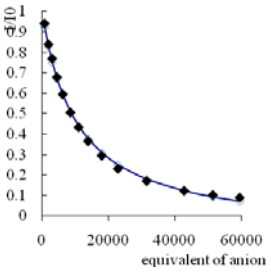


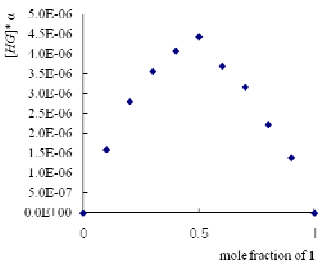




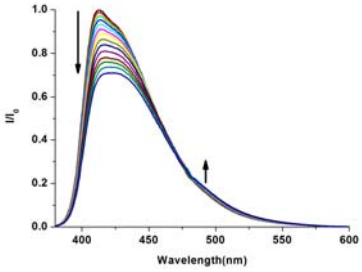
ii) **1** + $Bu_4N^+I^-$

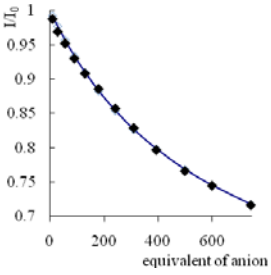


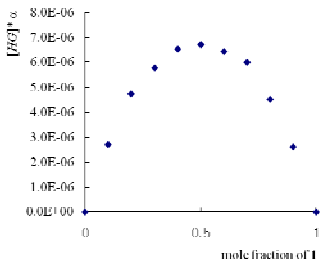




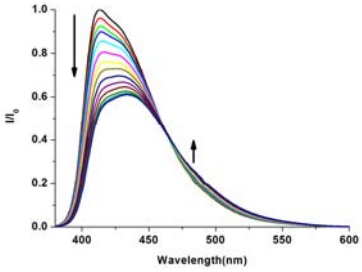
iv) **1** + $Bu_4N^+CN^-$

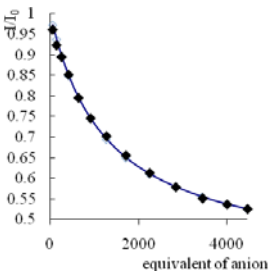


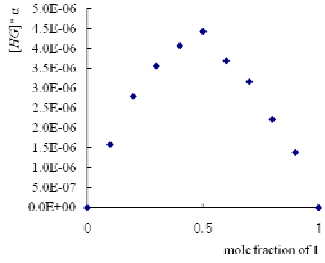




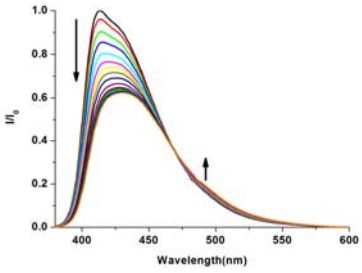
v) **1** + $Bu_4N^+N_3^-$

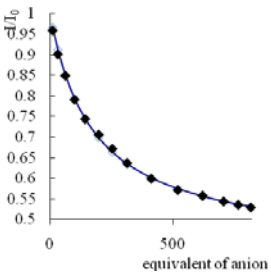


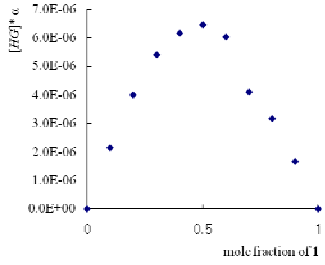




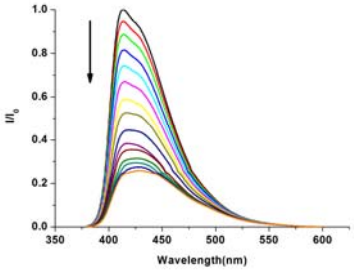
vi) **1** + $Bu_4N^+CH_3CO_2^-$

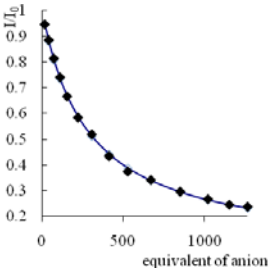


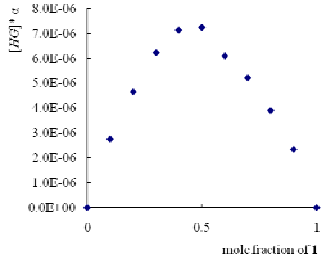




vii) **1** + $Bu_4N^+H_2PO_4^-$







4. X-ray crystallographic Analysis

A crystal of **1** was coated with paratone oil and the diffraction data measured at 99 K with synchrotron radiation (λ = 0.75000 Å) on a 6BMXW ADSC Quantum-210 detector with a Pt-coated Si double crystal monochromator at the Pohang Accelerator Laboratory, Korea. The ADSC Quantum-210 ADX program[4] was used for data collection, and HKL2000 (Ver. 0.98.698a)[5] was used for cell refinement, reduction and absorption correction.

The crystal structure of **1**·$(Bu_4N^+)_2SO_4^{2-}$ was solved by the direct method with SIR-92 of WINGX software package[6] and refined by full-matrix least-squares calculations with the SHELXTL software package.[7] One ligand ($C_{92}H_{92}N_6O_2$), one sulfate anion, two tetrabutyl ammonium (Bu_4N) cations, three additional ethyl acetate solvent molecules were observed as an asymmetric unit. Three oxygen atoms of the sulfate anion are rotationally disordered along an S-O bond. One terminal *t*-butyl residue of the ligand is also rotationally disordered in the crystal structure. One methyl group of a Bu_4N^+ and another methylene group of the other Bu_4N^+ are also statically disordered. Among three solvent ethyl acetates one is statically disordered. All non-hydrogen atoms were refined anisotropically. The hydrogen atoms involved in hydrogen bonding, which are attached to either N or O atoms, were found in difference Fourier Map and refined isotropically. The other hydrogen atoms were assigned isotropic displacement coefficients U(H) = 1.2U (C) or 1.5U (C_{methyl}), and their coordinates were allowed to ride on their respective atoms. The hydrogen atoms attached to the disordered carbon atoms were not included in the least-square refinement because of the divergence of their positional parameters. The carbonyl bond distance of the minor part of the disordered ethyl acetate molecule and the several carbon−carbon bond distances of the tetrabutyl ammonium cations and ethyl acetate molecules were restrained using DFIX during the least-squares refinement because of poor geometry. Refinement of the structure converged at a final $R1 = 0.0829$, $wR2 = 0.2193$ for 20072 reflections with $I > 2\sigma(I)$; $R1 = 0.1288$, $wR2 = 0.2544$ for all 30687 reflections. The largest difference peak and hole were 0.881 and

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[4] A. J. Arvai and C. Nielsen, ADSC Quantum-210 ADX Program, Area Detector System Corporation; Poway, CA, USA, 1983.
[5] Z. Otwinowski and W. Minor, in Methods in Enzymology, ed. Carter, Jr., C. W.; Sweet, R. M. Academic Press: New York, **1997**, *276*, *part A*, 307–326.
[6] WINGX program (Version 1. 70. 01), L. J. Farregia, *J. Appl. Cryst.*, **1999**, *32*, 837–838.
[7] G. M. Sheldrick, SHELXTL–PLUS, Crystal Structure Analysis Package; Bruker Analytical X-ray, Madison, WI, 1997.

–0.690 e·Å^{-3}, respectively. A summary of the crystal and some crystallography data is given in Table S2. CCDC-727661 contains the supplementary crystallographic data for this paper. The data can be obtained free of charge at www.ccdc.cam.ac.uk/conts/retrieving.html or from the Cambridge Crystallographic Data Centre, 12, Union Road, Cambridge CB2 1EZ, UK.

Table S2. Crystal data and structure refinement for **1**·$(Bu_4N^+)_2SO_4^{2-}$.

Identification code	**1**·$(Bu_4N^+)_2SO_4^{2-}$
Empirical formula	C_{136} H_{188} N_8 O_{12} S
Formula weight	2159.00
Temperature	99(2) K
Wavelength	0.75000 Å
Crystal system	Monoclinic
Space group	$P2_1/c$
Unit cell dimensions	a = 18.123(4) Å □ α= 90°.
	b = 40.036(8) Å □ β= 92.11(3)°.
	c = 17.059(3) Å □ γ= 90°.
Volume	12369(4) Å^3
Z	4
Density (calculated)	1.159 Mg/m^3
Absorption coefficient	0.089 mm^{-1}
F(000)	4688
Crystal size	0.35 x 0.33 x 0.25 mm^3
Theta range for data collection	1.60 to 30.00°.
Index ranges	-22<=h<=24, -52<=k<=53, -22<=l<=21
Reflections collected	108247
Independent reflections	30687 [R(int) = 0.0945]
Completeness to theta = 30.00°	100.0 %

Absorption correction	Semi-empirical from equivalents
Max. and min. transmission	0.9780 and 0.9694
Refinement method	Full-matrix least-squares on F^2
Data / restraints / parameters	30687 / 20 / 1555
Goodness-of-fit on F^2	1.038
Final R indices [I>2sigma(I)]	R1 = 0.0829, wR2 = 0.2193
R indices (all data)	R1 = 0.1288, wR2 = 0.2544
Largest diff. peak and hole	0.881 and -0.690 e.Å^{-3}

Table S3. Hydrogen bonds for **1**·$(Bu_4N^+)_2SO_4^{2-}$ [Å and °].

D-H...A	d(D-H)	d(H...A)	d(D...A)	<(DHA)
N(6)-H(6N)...O(32S)	0.82(3)	2.09(4)	2.912(9)	174(3)
N(6)-H(6N)...O(3S)	0.82(3)	2.03(3)	2.799(3)	156(3)
N(5)-H(5N)...O(3S)	0.89(4)	2.00(4)	2.844(3)	156(3)
N(5)-H(5N)...O(22S)	0.89(4)	1.99(4)	2.803(9)	151(3)
N(4)-H(4N)...O(42S)	0.83(4)	2.29(4)	2.932(13)	135(3)
N(4)-H(4N)...O(2S)	0.83(4)	1.98(4)	2.780(3)	165(3)
N(3)-H(3N)...O(4S)	0.85(3)	1.99(3)	2.829(3)	169(3)
N(3)-H(3N)...O(42S)	0.85(3)	1.79(3)	2.571(9)	152(3)
N(2)-H(2N)...O(1S)	0.93(4)	1.97(4)	2.816(3)	149(4)
N(1)-H(1N)...O(1S)	0.80(4)	2.06(4)	2.783(3)	150(4)
O(2)-H(2)...O(4S)	0.95(5)	2.10(4)	2.883(4)	138(4)
O(2)-H(2)...O(32S)	0.95(5)	2.08(5)	2.956(10)	152(4)
O(1)-H(1)...O(2S)	0.860(19)	1.99(3)	2.810(3)	160(5)
O(1)-H(1)...O(22S)	0.860(19)	1.81(3)	2.568(9)	146(5)

Symmetry transformations used to generate equivalent atoms

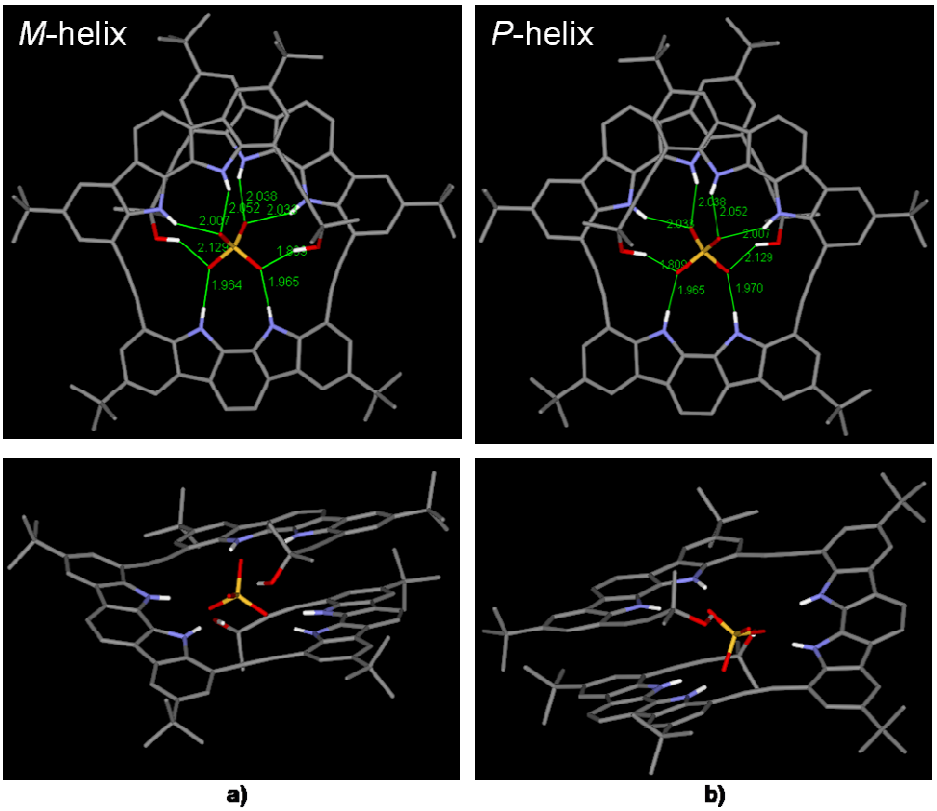

Figure S6. Top and side views of the crystal structure of **1**·$(Bu_4N^+)_2SO_4^{2-}$ showing hydrogen bonds. Hydrogen atoms except NHs have been omitted for clarity. a) left handed helix, b) right handed helix.

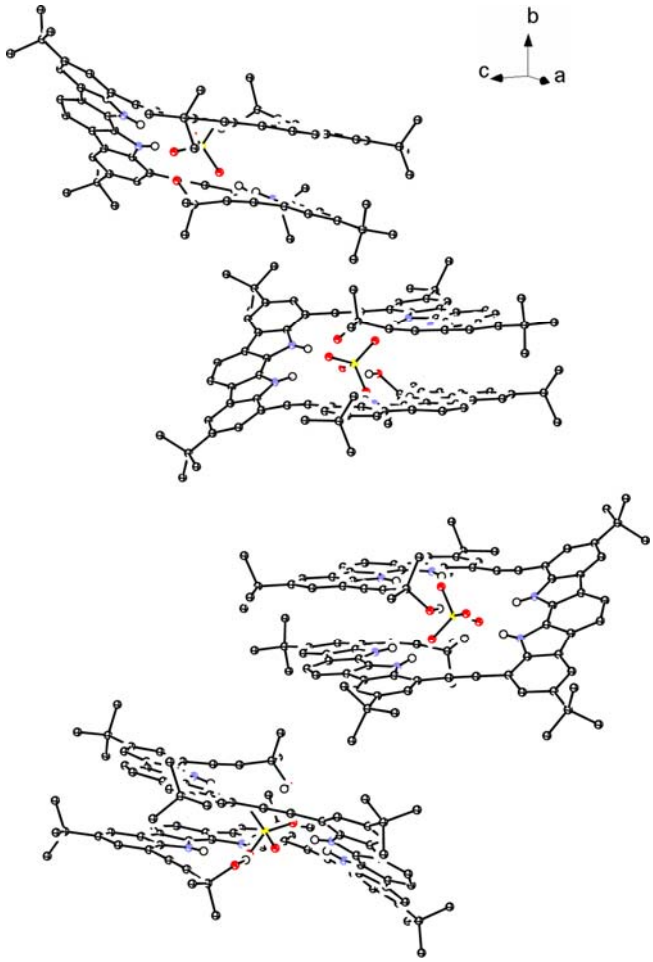

Figure S7. ORTEP plots for the crystal structure of **1**·$(Bu_4N^+)_2SO_4^{2-}$ showing the unit cell diagram. Displacement ellipsoids are scaled to the 20% probability level. Hydrogen atoms except NH, OH hydrogens have been omitted for clarity. Four tetrabutylammonium cations, not shown here, are located on the aromatic planes, between indolocarbazole surfaces.