Electronic Supplementary Information

A bis-bisurea receptor with the *R*,*R*-cyclohexane-1,2-diamino spacer for phosphate and sulfate ions

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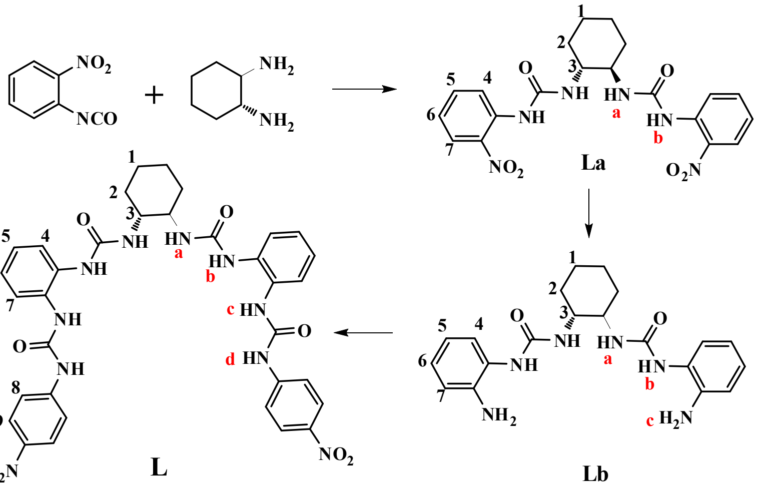
S1. General

All tetrabutylammonium salts and *p*-nitrophenylisocyanate were purchased from Alfa Aesar and used as received. Solvents and other reagents were of reagent grade quality. ^{1}H, ^{31}P and ^{13}C NMR spectra were recorded on a Mercury plus-400 spectrometer at 400, 100, and 162 MHz, respectively. UV-vis spectra were performed on an HP8453 spectrophotometer (1-cm quartz cell). Elemental analyses were performed on an Elementar VarioEL instrument. IR spectra were recorded on a Bruker IFS 120HR spectrometer. ESI-MS measurements were carried out using a Waters ZQ4000 spectrometer. Melting points were detected on an X-4 Digital Vision MP Instrument. Circular dichroism spectra were performed on a Jasco J-810 Circular Dichroism Chiroptical Spectrometer.

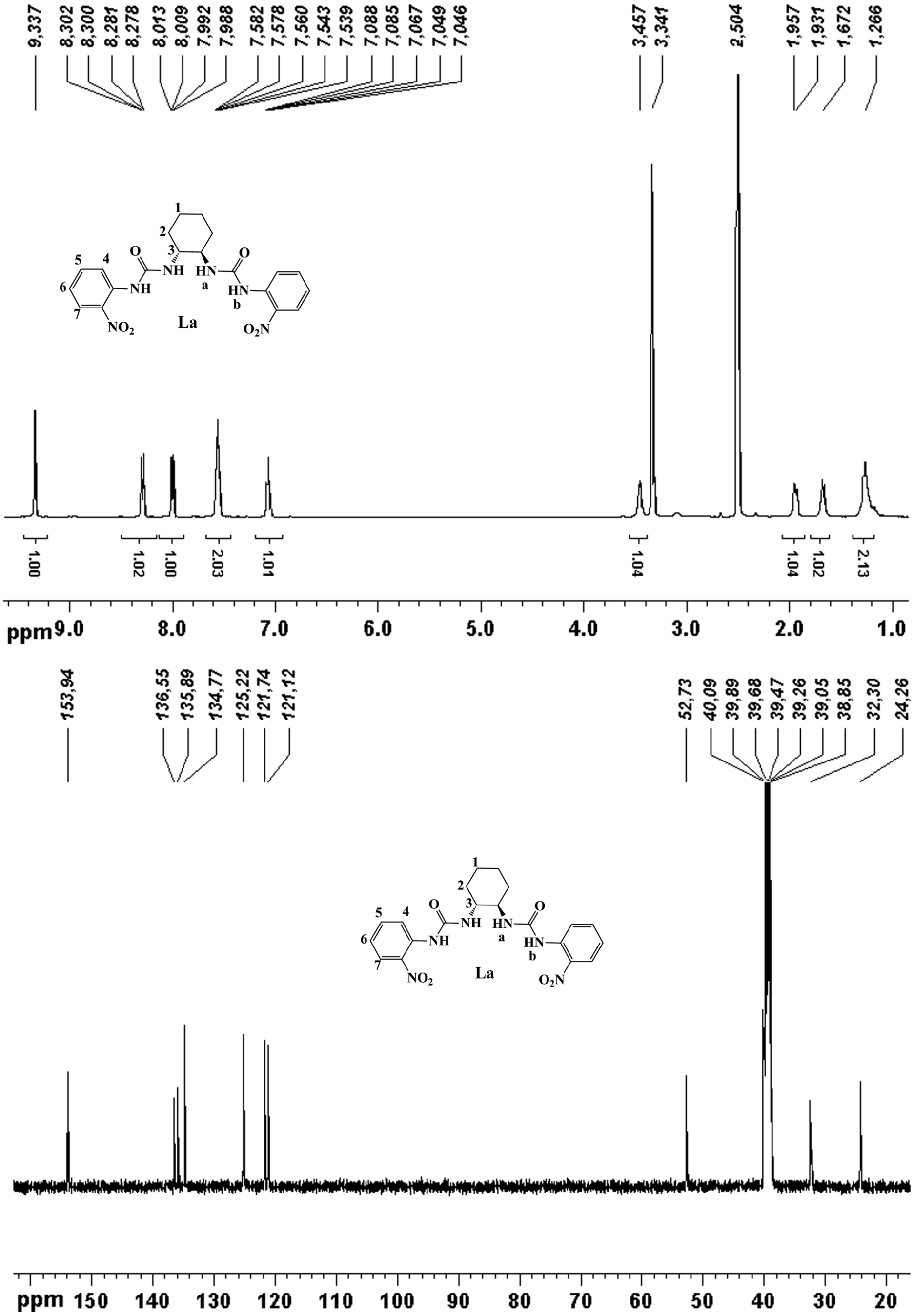
S2. Synthesis and ^{1}H and ^{13}C NMR spectra of the ligand L



Scheme S1. Synthesis of **L**: (1) THF; (2) $NH_2NH_2{\cdot}H_2O$, Pd/C 10% cat., MeOH; (3) *p*-nitrophenylisocyanate, THF.

1,1-Bis-(2-nitrophenylurea)-(1R,2R)-cyclohexane (La).

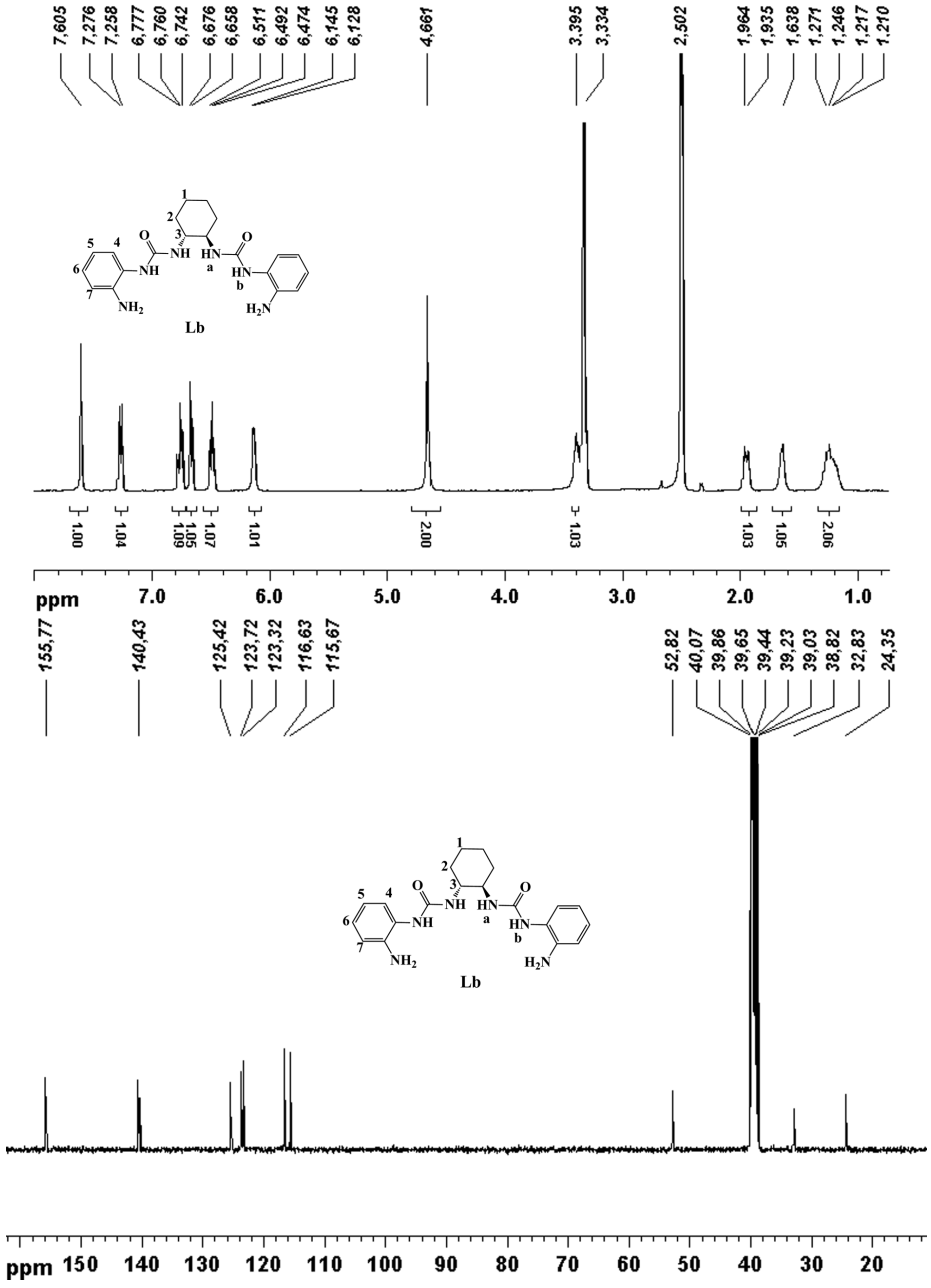
A solution of *R*,*R*-cyclohexane-1,2-diamine (0.29 g, 2.5 mmol) in 50 mL THF was added dropwise to a THF solution (100 mL) of *o*-nitrophenylisocyanate (0.98 g, 6.0 mmol). After refluxing under stirring for 10 hours, the mixture was concentrated and filtered off, and washed with acetone and diethyl ether and then dried in vacuum to yield compound **La** as a yellow solid (1.02 g, 91 %). M.p.: > 300 °C. ^{1}H NMR (400 MHz, DMSO-d_6, ppm): δ 9.34 (s, 2H, Hb), 8.29 (d, J = 8.4 Hz, 2H, H7), 8.00 (d, J = 8.4 Hz, 2H, H4), 7.56 (m, 4H, H6+Ha), 7.07 (t, J = 8.4 Hz, 2H, H5), 3.46 (s, 2H, H3), 1.94 (d, J = 10.4 Hz, 2H, H2), 1.67 (s, 2H, H2),1.27 (s, 4H, H1). ^{13}C NMR (100 MHz, DMSO-d_6), 153.9 (CO), 136.5 (C), 135.8 (C), 134.7 (CH), 125.2 (CH), 121.7 (CH), 121.2 (CH), 52.7 (CH), 32.3 (CH_2), 24.2 (CH_2). IR (KBr, ν/cm^{-1}): 3294, 3083, 1650, 1581, 1511, 1339, 1281. Anal. Calcd for $C_{20}H_{22}N_6O_6$: C, 54.29; H, 5.01; N, 19.00%. Found: C, 54.26; H, 5.01; N, 18.96%. ESI-MS: *m/z* 443.2, 100%, $[M + H]^+$.



^{1}H NMR and ^{13}C NMR spectra of **La** (r.t., DMSO-d_6)

1,1-Bis-(2-aminophenylurea)-(1R,2R)-cyclohexane (Lb).

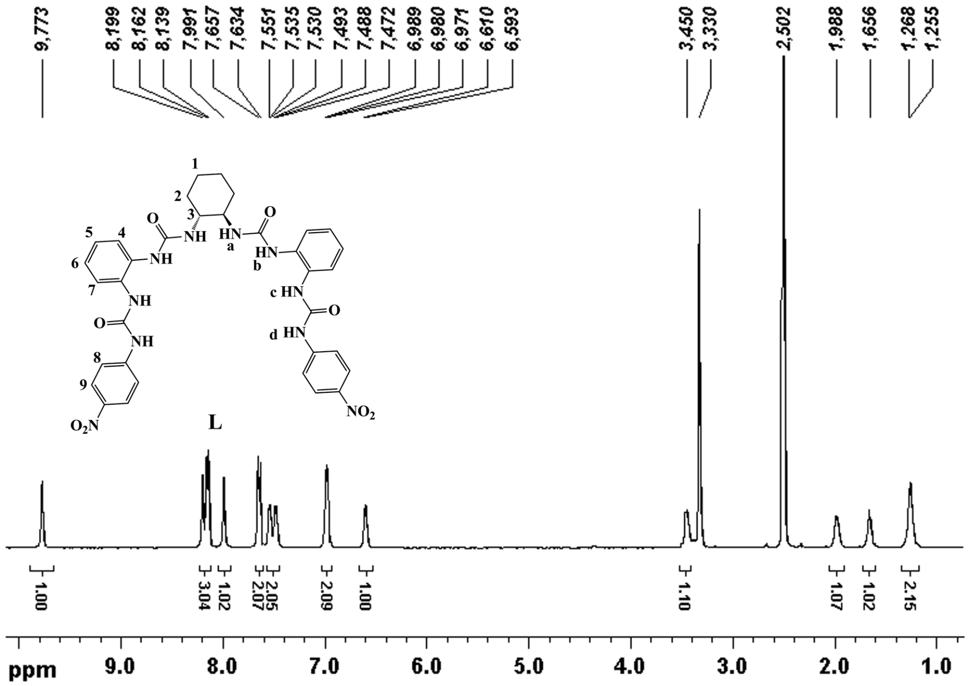
Hydrazine monohydrate (5.0 mL) was added dropwise to a suspension of 1,1-bis-(2-nitrophenyl-urea)-(1*R*,2*R*)-cyclohexane (**a**, 1.00 g, 2.3 mmol) and 10% Pd/C (0.05 g, cat.) in methanol (150 mL). After refluxing under intense stirring for 12 hours, the solid was filtered off and then dissolved in DMSO (40 mL) and filtered through Celite to remove Pd/C. The DMSO solution was poured in water (400 mL) and the precipitate thus obtained was filtered off, washed several times with ethanol and diethyl ether, and dried over vacuum to give pure **Lb** as a white solid (0.70 g, 81 %). M.p.: 279 °C. ^{1}H NMR (400 MHz, DMSO-d_6, ppm): δ 7.61 (s, 2H, Hb), 7.26 (d, J = 7.2 Hz, 2H, H4), 6.76 (t, J = 7.2 Hz, 2H, H5), 6.67 (d, J = 7.2 Hz, 2H, H7), 6.49 (t, J = 7.6 Hz, 2H, H6), 6.13 (d, J = 6.8 Hz, 2H, Ha), 4.66 (s, 4H, Hc), 3.40 (s, 2H, H3), 1.95 (d, J = 11.6 Hz, 2H, H2), 1.64 (s, 2H, H2), 1.23 (m, 4H, H1). ^{13}C NMR (100 MHz, DMSO-d_6), 155.7 (CO), 140.4 (C), 125.4 (C), 123.7 (CH), 123.3 (CH), 116.6 (CH), 115.6 (CH), 52.8 (CH), 32.8 (CH$_2$), 24.3 (CH$_2$). IR (KBr, ν/cm^{-1}): 3285, 3112, 1625, 1585, 1508, 1306, 1277. Anal. Calcd for $C_{20}H_{26}N_6O_2$: C, 62.81; H, 6.85; N, 21.97%. Found: C, 62.84; H, 6.63; N, 21.97%. ESI-MS: m/z 383.3, 100%, [M + H]$^+$.

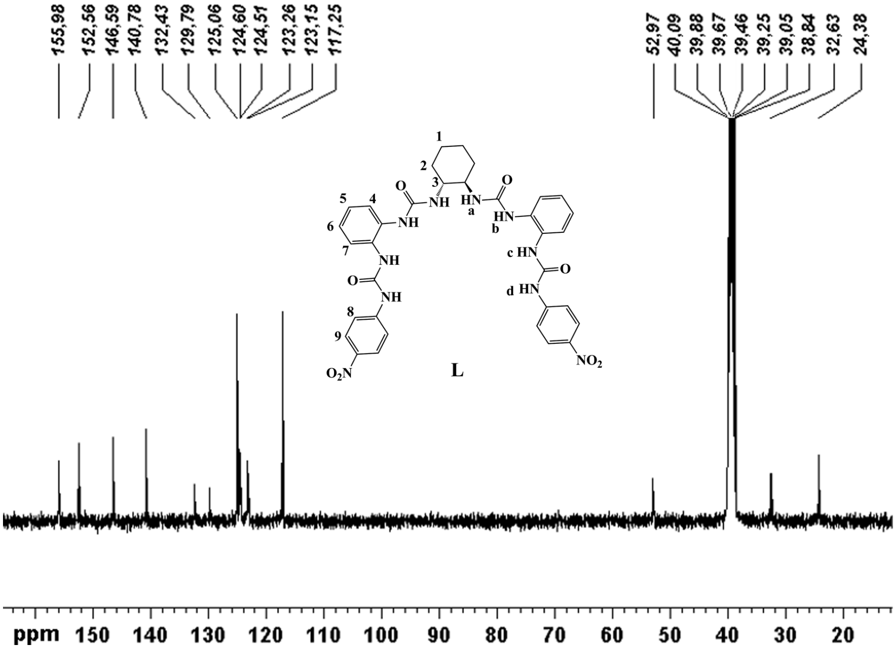


^{1}H NMR and ^{13}C NMR spectra of **Lb** (r.t., DMSO-d_6)

1,1-((1R,2R)-cyclohexane-1,2-diyl)bis(3-(2-(3-(4-nitrophenyl)ureido)phenyl)urea) (L).

1,1-Bis-(2-aminophenyl-urea)-(1*R*,2*R*)-cyclohexane (**Lb**, 0.20 g, 0.5 mmol) was dispersed in 60 mL THF and added dropwise into a 60 mL THF solution of *p*-nitrophenylisocyanate (0.20 g, 10.0 mmol). The mixture was refluxed for 12 hours and then concentrated. The crude product was poured in water (150 mL) and the precipitate thus obtained was filtered off, washed several times with methanol and diethyl ether and then dried over vacuum to give **L** as a yellow solid (0.34 g, 92%). M.p.: 237 °C. ^{1}H NMR (400 MHz, DMSO-d_6, ppm): δ 9.77 (s, 2H, Hd), 8.20 (s, 2H, Hc), 8.15 (d, J = 9.2 Hz, 4H, H9), 7.99 (s, 2H, Hb), 7.65 (d, J = 9.2 Hz, 4H, H8), 7.55 (m, 2H, H7), 7.49 (m, 2H, H4), 6.99 (m, 4H, H5+H6), 6.60 (s, 2H, Ha), 3.45 (s, 2H, H3), 1.99 (s, 2H, H2), 1.66 (s, 2H, H2), 1.26 (m, 4H, H1). ^{13}C NMR (100 MHz, DMSO-d_6, ppm), ^{13}C NMR (100 MHz, DMSO-d_6), 155.9 (CO), 152.5 (CO), 146.5 (C), 140.7 (C), 132.4(C), 129.7 (CH), 125.0 (C), 124.6 (CH), 124.5 (CH), 123.2 (CH), 123.1 (CH), 117.2 (CH), 52.9 (CH), 32.6 (CH$_2$), 24.3 (CH$_2$). IR (KBr, ν/cm^{-1}): 3307, 3088, 1645, 1598, 1561, 1504, 1331, 1302, 1260. Anal. Calcd for $C_{34}H_{34}N_{10}O_8$: C, 57.46; H, 4.82; N, 19.71%. Found: C, 57.60; H, 4.67; N, 19.46%. ESI-MS: *m/z* 711.3, 100%, [M + H]$^+$.





^{1}H NMR and ^{13}C NMR spectra of **L** (r.t., DMSO-d_6)

S3. X-ray crystallography

Diffraction data were collected on a Bruker SMART APEX II diffractometer at 150 K or 100 K with graphite-monochromated Mo Kα radiation (λ = 0.71073 Å). An empirical absorption correction using SADABS was applied for all data. The structures were solved by direct methods using the SHELXS program. All non-hydrogen atoms were refined anisotropically by full-matrix least-squares on *F*2 by the use of the SHELXL program. Hydrogen atoms bonded to carbon and nitrogen were included in idealized geometric positions with thermal parameters equivalent to 1.2 times those of the atom to which they were attached.

Table S1. Crystal data and structure refinement details for the anion complexes **1** and **2**.

Formula	$C_{140}H_{234}N_{24}O_{28}P_2$	$C_{134}H_{217}N_{24}O_{25}S_3$
M	2763.45	2660.50
Crystal system	Monoclinic	Triclinic
Space group	*P*2(1)	*P*1
a /Å	16.201(8)	12.821(3)
b /Å	14.693(7)	16.131(4)
c /Å	31.511(15)	19.300(4)
α /°	90.00	77.453(2)
β /°	100.528(7)	77.365(3)
γ /°	90.00	87.544(3)
V /Å^3	7375(6)	3801.9(15)

Z	2	1
T /K	150(2)	100(2)
$F(000)$	2992	1437
D_{calc} /g cm^{-3}	1.244	1.162
μ /mm^{-1}	0.11	0.12
R(int)	0.082	0.028
Data/restraints/parameters	22279/1/1769	20732/3/1693
GOF	1.04	1.05
$R1$ $[I > 2\sigma(I)]$	0.071	0.079
$wR2$ $[I > 2\sigma(I)]$	0.197	0.239
Flack parameter	0.07(14)	-0.03(9)

Table S2. Hydrogen bonds around the HPO_4^{2-} ion in complex **1**.

D−H···A	*d*(D−H) (Å)	*d*(H···A) (Å)	*d*(D···A) (Å)	∠(DHA) (°)
N2−H2···O22	0.88	1.84	2.694(6)	163.3
N3−H3···O22	0.88	2.21	2.999(6)	148.3
N4−H4···O21	0.88	2.04	2.868(6)	155.7
N5−H5A···O21	0.88	2.24	2.910(5)	132.5
N6−H6A···O24	0.88	2.02	2.827(5)	152.5
N7−H7···O24	0.88	2.08	2.893(5)	152.2
N8−H8···O22	0.88	1.92	2.787(6)	167.4
N9−H9A···O23	0.88	2.15	2.997(7)	161.6
N12−H12A···O19	0.88	1.84	2.685(5)	161.6
N13−H13···O19	0.88	2.12	2.909(6)	148.4
N14−H14···O18	0.88	2.15	2.954(5)	151.3
N15−H15A···O18	0.88	2.07	2.839(5)	146.1
N16−H16···O17	0.88	2.14	2.884(5)	141.5
N17−H17···O17	0.88	2.02	2.852(5)	157.6
N18−H18···O19	0.88	2.02	2.898(7)	173.7
N19−H19···O17	0.88	2.30	3.083(6)	148.7
N19−H19···O20	0.88	2.54	3.324(7)	149.2
O20−H201···O21	0.86	1.84	2.640(5)	154.6
O23−H231···O18	1.10	1.97	2.604(6)	113.1
O25−H251···O20	1.08	1.90	2.946(6)	160.7
O25−H252···O24	1.10	1.92	2.712(6)	125.6
O26−H261···O17	0.71	2.07	2.729(6)	156.7
O26−H262···O21	0.68	2.24	2.900(7)	163.7

Table S3. Hydrogen bonds around the SO_4^{2-} ion in complex **2**.

D−H···A	*d*(D−H) (Å)	*d*(H···A) (Å)	*d*(D···A) (Å)	∠(DHA) (°)
N2−H2A···O17	0.88	2.27	3.125	162.7
N3−H3A···O20	0.88	2.73	3.260	120.2
N3−H3···O18	0.88	1.94	2.822	177.6
N4−H4···O20	0.88	2.14	2.945	152.2
N5−H5A···O20	0.88	2.11	2.866	143.7
N6−H6A···O19	0.88	2.05	2.863	153.5
N7−H7···O19	0.88	2.38	3.105	139.9
N8−H8···O18	0.88	1.95	2.791	160.2
N9−H9A···O17	0.88	2.03	2.900	167.6
N12−H12A···O21	0.88	2.41	3.135	139.3
N12−H12A···O22	0.88	2.39	3.236	160.4
N13−H13···O21	0.88	1.88	2.745	169.5
N14−H14···O23	0.88	2.22	2.987	145.2
N15−H22F···O23	0.88	2.14	2.870	139.9
N16−H16···O24	0.88	2.06	2.873	152.9
N17−H17···O24	0.88	2.25	3.043	149.4
N18−H25B···O21	0.88	1.95	2.826	170.4
N19−H19···O22	0.88	2.07	2.927	165.0
C89−H89A···O19	0.99	2.35	3.322	165.5
C93−H93B···O17	0.99	2.53	3.493	165.7
C117−H23F···O22	0.99	2.52	3.469	160.2
C122−H12S···O23	0.99	2.66	3.479	140.3
C129−H12D···O23	0.99	2.33	3.307	171.6

S4. NMR titrations

For ^{1}H NMR Job's plot: Stock solutions of **L** (5 mM) and anion (5.0 mM for $H_2PO_4^-$ and SO_4^{2-}) in DMSO-d_6 (5.0 mL) were prepared in separate volumetric flasks. Ten 5 mm-o.d. NMR tubes were separately filled with a total of 500 μL solution of the host and guest in the following ratios (μL, host/guest) at 297 K: 10:0, 9:1, 8:2, 7:3, 6:4, 5:5, 4:6, 3:7, 2:8, 1:9. The ^{1}H NMR spectra were obtained for each tube and the NHc signals were used to calculate the complex concentration, $[HG] = [H]_t \times (\delta_{obsd} - \delta_{free})/(\delta_{com} - \delta_{free})$, where $[H]_t$ is the total concentration of the host, δ_{obsd} is the chemical shift observed on every point, δ_{free} and δ_{com} correspond to the chemical shifts of the free ligand and the complex. This value was plotted against the molar fraction of the host. The association constants (K) were determined by EQNMR.

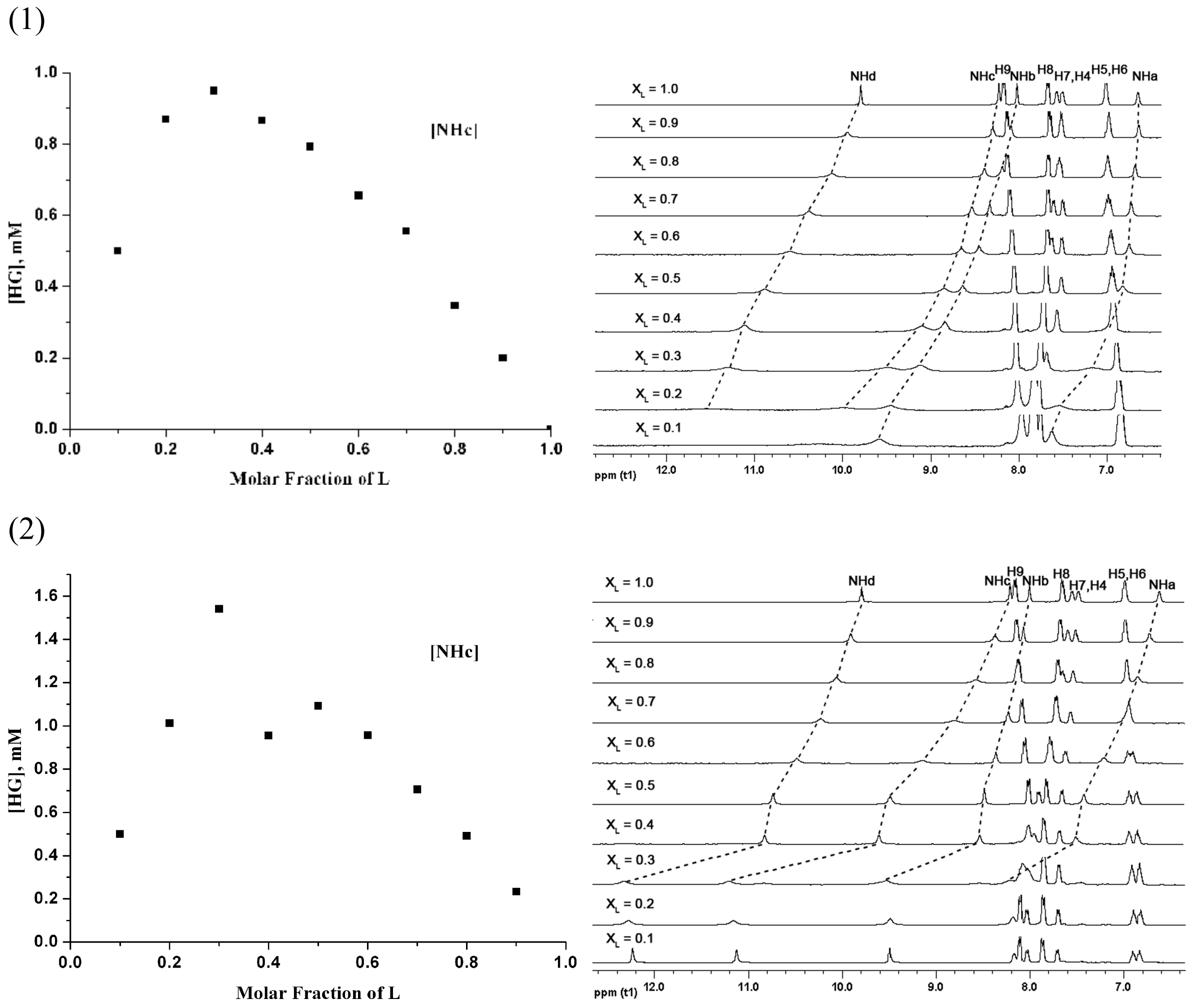


Figure S1. Job's plot of **L** with addition of anions and the corresponding ^{1}H NMR spectra. (1) $H_2PO_4^-$ (as Bu_4N^+ salt, DMSO-d_6); (2) SO_4^{2-} (as Bu_4N^+ salt, DMSO-d_6).

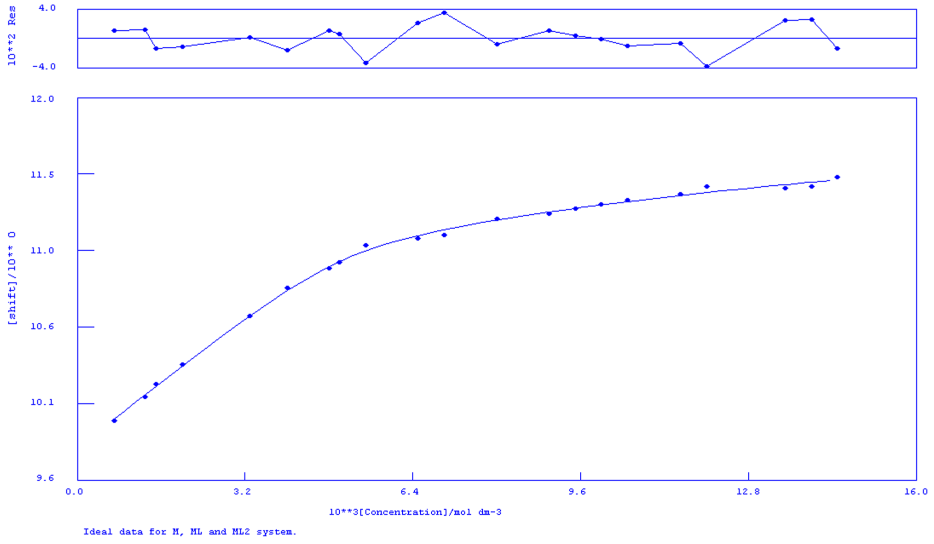


Figure S2. NMR titration of **L** (5.0×10^{-3} M) with $(Bu_4N)H_2PO_4$ (5.0×10^{-3} M) in DMSO-d_6.

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Calculations by WinEQNMR Version 1.20 by Michael J. Hynes
Program run at 10:41:54     on 04/23/2012

 Ideal data for M, ML and ML2 system.
 IDEAL DATA TAKEN FROM ACTUAL FIT of JIMMY1.FIT
 Reactions:   M + L = ML (beta1 = K1);     M + 2L = ML2 (beta2 = K1K2)
 Theoretical: k1=7290.00, k1k2 =400000.00 del ML = 10.9637, del ML2 = 11.3277
 File prepared by M.J. Hynes october 22 2000

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   3   1   9.79966E+00     1.000E-01   1.534E-02    1.337E+00     M SHIFT
   4   1   1.11209E+01     1.000E-01   1.622E-02    6.355E+00     ML SHIFT
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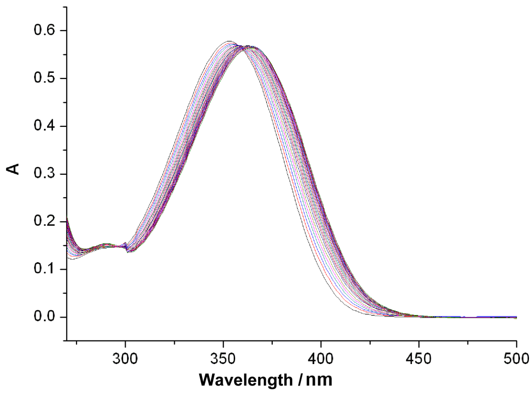
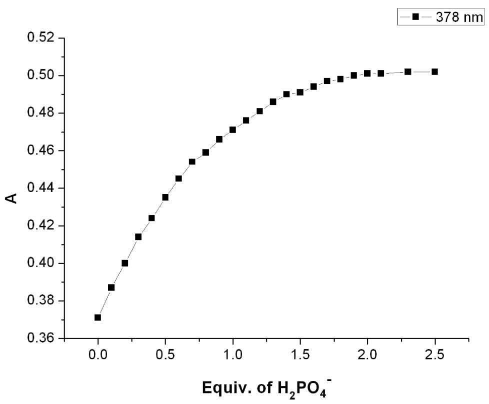
S5. UV-vis titrations

Stock solutions of **L** (1.5×10^{-5} M) in DMSO (100 mL) and anions in DMSO (2 mL, 1.5–50 mM) were prepared for the UV-vis titration. Small portions (2–5 μL) of the anion solutions ($H_2PO_4^-$ and SO_4^{2-}) were added to the solution of ligand **L** (2.0 mL), and the spectrum was recorded after each addition.





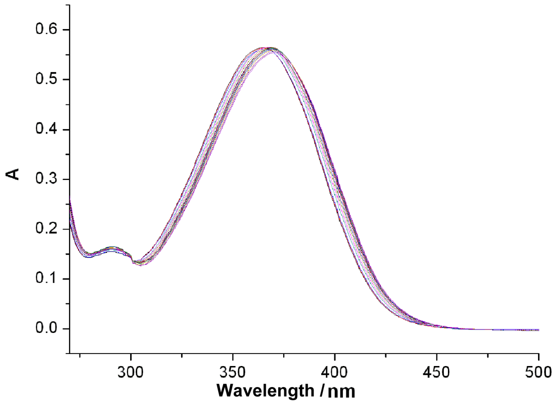


Figure S3. UV-vis titration of **L** (1.5 × 10^{-5} M) with $H_2PO_4^-$ (as Bu_4N^+ salt) in DMSO (above: before 2.5 equivalents; below: 2.5 to 100.0 equivalents).

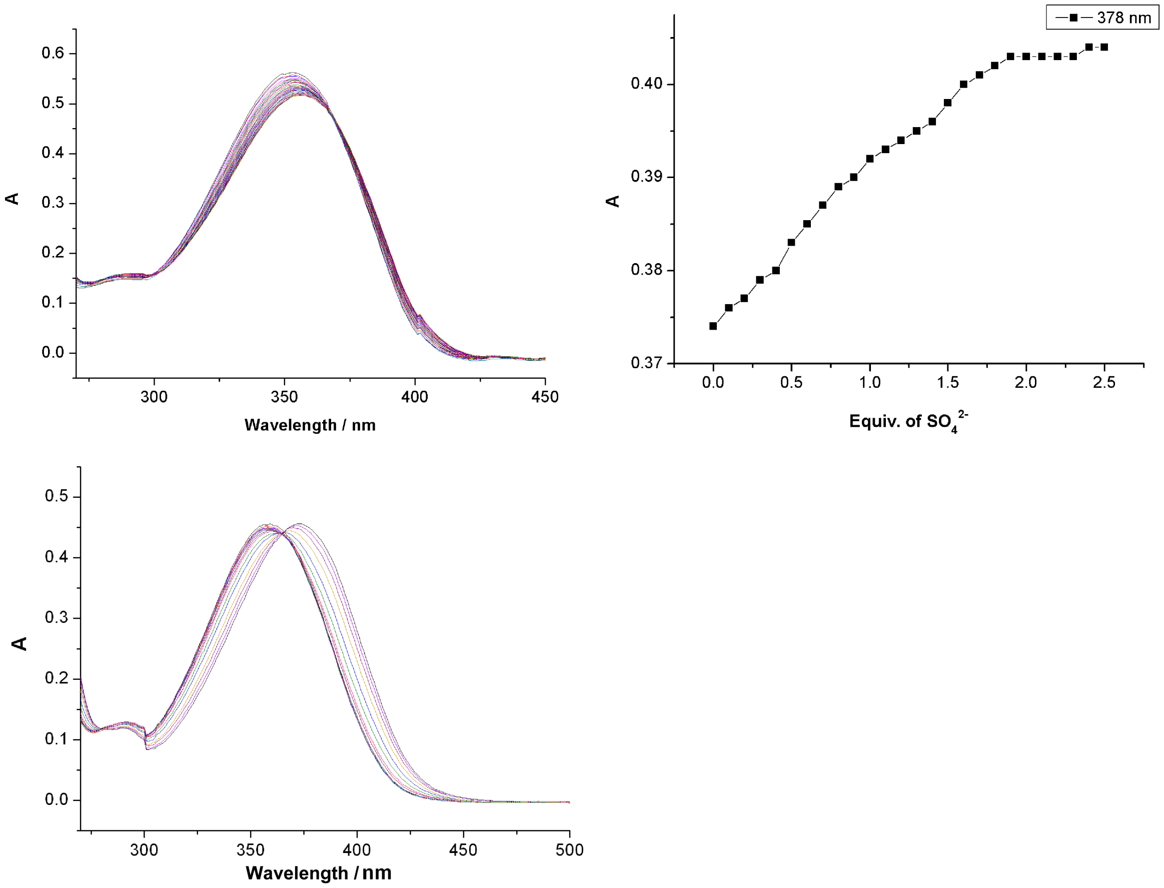


Figure S4. UV-vis titration of **L** (1.5 × 10^{-5} M) with SO_4^{2-} (as Bu_4N^+ salt) in DMSO (above: before 2.5 equivalents; below: 2.5 to 150.0 equivalents).

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DATA

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REACTION MECHANISM

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P.D.D <===> D + P.D : K2 dissoc

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	K2	0.01	0.002874	0.00023	8
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	r:P.D.D	28.15	31.05	0.032	0.1

$K_1 = 1/K1 = 28.1\ (mM^{-1}) = 2.81 \times 10^4\ (M^{-1})$

$K_2 = 1/K2 = 347.9\ (mM^{-1}) = 3.47 \times 10^5\ (M^{-1})$

$\beta = K_1 \cdot K_2 = 9.75 \times 10^9\ (M^{-2})$

S6. CD studies

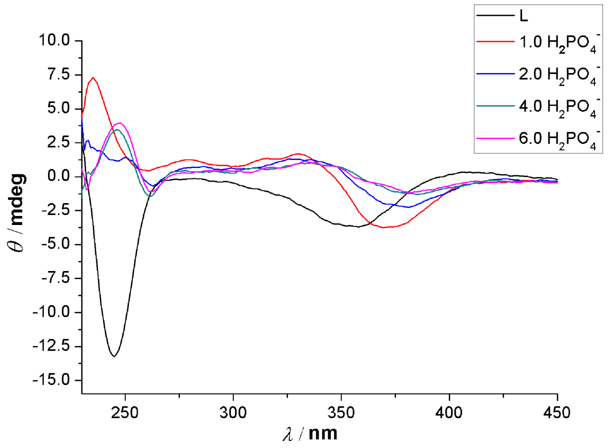

Figure S5. CD spectra of **L** (1.5×10^{-4} M) upon addition of $H_2PO_4^-$ ions (as Bu_4N^+ salt) in CH_3CN-0.5% DMSO.

S7. Computational details

The DFT calculations on the free ligand was performed at B3LYP/6-311++G (d, p) level using the Gaussian 03 program.[1] Input parameters are built by Gauss View.

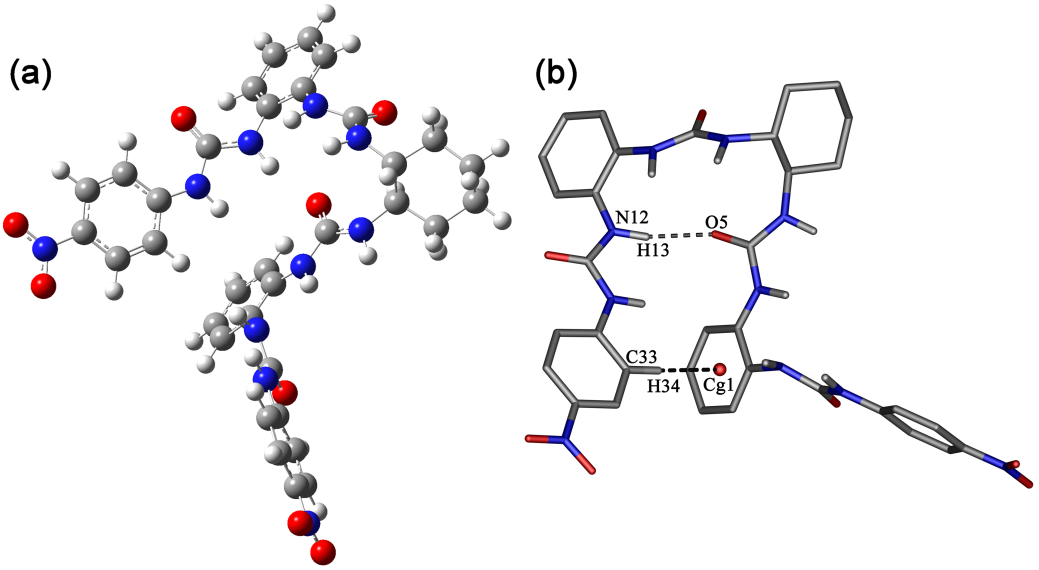

Figure S6. (a) Optimized geometry for the free ligand **L**; (b) Intramolecular hydrogen bonding and C–H···π interactions in **L** (Cg1 represents the centroid of the *o*-phenylene ring, C33···Cg1 = 3.711 Å, ∠Cg1···H34–C33 = 164.7º, N12···O5 = 3.099 Å, ∠O5···H13–N12 = 168.6º).

Cartesian coordinates (Å) for the optimized geometry of **L**.

E = −2465.40122921 hartree

O	10.0116	2.3171	31.8133
O	8.8644	3.9686	31.0121
O	12.7444	0.0235	26.0528
O	12.2247	0.6803	19.1206
O	12.7134	5.0676	19.0626
O	10.9681	7.9269	25.0713
O	5.7399	6.5501	29.9712
O	7.331	7.7564	30.7466
N	9.6701	3.0415	30.8702
N	11.561	1.9674	25.7693
H	11.3642	2.583	25.1717
N	12.3642	0.8404	23.9665
H	11.9555	1.4899	23.5328
N	11.644	0.5348	21.3301
H	11.0625	0.8302	21.9218
N	10.1717	1.3473	19.7935
H	9.5555	1.2107	20.4069
N	10.7442	4.1214	19.5549
H	10.0718	4.0832	20.1219
N	11.634	5.5995	21.0178
H	10.9238	5.4085	21.5005
N	11.4656	6.1711	23.7023
H	11.3025	5.3218	23.5421
N	9.7481	6.0462	25.2197
H	9.5421	5.2983	24.803
N	6.8475	7.0717	29.8786
C	10.2055	2.7814	29.5672
C	11.1911	1.8587	29.4334
H	11.5476	1.4267	30.1998
C	11.6699	1.5501	28.1818
H	12.3572	0.9022	28.0839
C	11.1486	2.1863	27.0553
C	10.1585	3.1414	27.2049
H	9.7991	3.5836	26.445

C	9.6904	3.4514	28.4943
H	9.0245	4.117	28.6167
C	12.2674	0.8522	25.3241
C	13.0507	-0.1058	23.193
C	14.0477	-0.8992	23.7212
H	14.2632	-0.8419	24.645
C	14.719	-1.7617	22.9163
H	15.3892	-2.3259	23.285
C	14.4391	-1.8278	21.5717
H	14.9402	-2.4097	21.011
C	13.4553	-1.0711	21.042
H	13.2651	-1.1358	20.1126
C	12.7259	-0.2116	21.8196
C	11.4039	0.8507	19.9976
C	9.8168	2.1011	18.6085
H	8.9025	2.4728	18.7773
C	9.7034	1.2386	17.3534
H	10.5857	0.839	17.1477
H	9.0623	0.5025	17.5164
C	9.2405	2.057	16.1827
H	8.3277	2.3964	16.3608
H	9.2042	1.484	15.3756
C	10.1623	3.2178	15.9299
H	9.8205	3.7526	15.1712
H	11.061	2.8798	15.6885
C	10.2658	4.0891	17.1518
H	9.3835	4.4975	17.3398
H	10.9116	4.8193	16.9804
C	10.7206	3.2912	18.3659
H	11.6466	2.9562	18.1949
C	11.7537	4.931	19.8068
C	12.4896	6.5134	21.5398
C	13.4301	7.1937	20.7681
H	13.4973	7.0086	19.8399
C	14.2577	8.1238	21.3363
H	14.8979	8.5704	20.7941
C	14.1823	8.4264	22.6747
H	14.7487	9.0891	23.0526
C	13.2742	7.7535	23.4634
H	13.2325	7.9342	24.3941
C	12.4397	6.8367	22.9154
C	10.7688	6.7911	24.6964
C	9.0092	6.3679	26.3542
C	9.5509	7.1335	27.397
H	10.4204	7.5067	27.3124
C	8.8293	7.3362	28.525
H	9.2116	7.8211	29.2487
C	7.5683	6.8543	28.6328
C	7.0258	6.1152	27.6374
H	6.1402	5.7802	27.7214
C	7.7627	5.8463	26.4967
H	7.3957	5.2983	25.813

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