Unusual recognition of $(n\text{-}Bu_4N)_2SO_4$ by a cyanuric acid based host *via* contact ion-pair interactions†

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Received 12th July 2010, Accepted 27th July 2010
DOI: 10.1039/c0cc02509g

A tripodal neutral receptor selectively binds tetrabutylammonium sulfate where anion is encapsulated in the cavity and cations are in close contact with the anion *via* C–H···O interactions. This organic cation capped sulfate-bowl exists both in solid and solution states and the sulfate assisted cap can be opened and closed reversibly with a temperature key.

Ion-pair recognition is important for its great potential in biological, analytical, and environmental applications.[1] It can also play an important role in controlling the geometry of self-assembly, enhancement of the binding affinity as the result of allosteric effects and enhanced electrostatic interactions between the co-bound ions, and even reversing the binding selectivity of the host.[2] Several strategies have been developed to achieve recognition of the ionic subunits of the guest salt where different modes like contact ion-pairs, solvent-bridged ion-pairs and host-separated ion-pairs have been employed.[3] Recently, C–H···anion interactions involving organic cations have attracted much attention because of their biological and chemical relevance.[4] However, reports on the interaction between anions and non-aromatic CH groups as hydrogen bond donors are rare in the literature.[5] On the other hand, tripodal,[6] cyclic,[7] macrobicyclic[8] and metal–organic[9] receptors are employed for binding and separation of sulfate and have also been used as templates for the formation of complex molecular structures.[10] Herein we report a tripodal urea receptor functionalized with pentafluorophenyl side arms on a rigid cyanuric acid platform as an effective receptor for tetrabutylammonium sulfate, $(n\text{-}Bu_4N)_2SO_4$ as an associated ion-pair where sulfate shows a coordination number of eleven. Further, we also demonstrate selective sulfate assisted contact ion-pair formation and temperature dependent dissociation/association of the ion-pair in solution by diffusion NMR measurements. To the best of our knowledge this report shows the first example of the binding of $(n\text{-}Bu_4N)_2SO_4$ as a contact ion-pair by a simple synthetic host in a polar solvent as well as in the solid state.

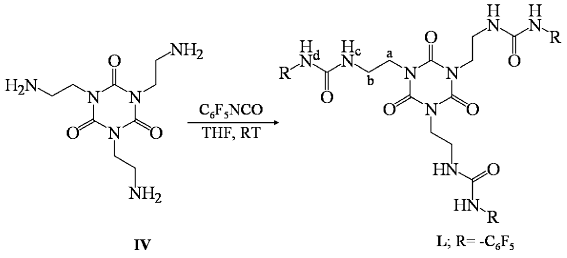
The synthesis of tripodal urea receptor **L** based on a cyanuric acid platform with pentafluorophenyl pendant arms is shown in Scheme 1. Reaction of the precursor triamine **IV** with 3.0 equivalents of pentafluorophenyl isocyanate in tetrahydrofuran (THF) results in the tripodal urea receptor, **L** in high yield.† The triamine **IV** is synthesized following the modified literature procedure.[11]

First evidence on the recognition of $(n\text{-}Bu_4N)_2SO_4$ by **L** *via* strong contact ion-pair interactions is obtained from the single crystal X-ray structural analysis of **1**.‡ The single crystal of sulfate complex, **1** is grown from dimethyl formamide (DMF) solution as $[L(SO_4^{2-})(n\text{-}Bu_4N^+)_2]\cdot DMF$ in good yield upon slow evaporation of **L** in the presence of $(n\text{-}Bu_4N)_2SO_4$.

Complex **1** crystallizes in the monoclinic system with the *Cc* space group. Three arms of the tripodal receptor form a cavity that completely encapsulates the sulfate in its centre *via* N–H···O hydrogen bonding interactions to all six –NH protons of the three urea groups of **L** (Fig. 1).† Interestingly, both the $n\text{-}Bu_4N^+$ counter cations are in close contact with the encapsulated SO_4^{2-} *via* five strong C–H···O interactions with its acidic $–CH_2$ group, adjacent to the cationic bridge-head nitrogen (Fig. 1).† Thus, encapsulated sulfate is in eleven hydrogen bonding interactions (Fig. 1) which represents an uncommon eleven coordination number in anion coordination chemistry.[12] Fig. 2 shows the space filling model of **1** which clearly depicts that the SO_4^{2-} is completely encapsulated in the cavity of **L** where both the $n\text{-}Bu_4N^+$ cations act as a cap of the sulfate-bowl. Thus, **L**, SO_4^{2-} and two $n\text{-}Bu_4N^+$ ions assembled together to an elliptical shaped (major axis of 17 Å and minor axis of 14 Å) aggregation in the solid state.

The complex **1** was subjected to ESI mass analysis in CH_3CN (negative mode).† The peak at *m*/*z* 1223.3 and its isotopic distribution pattern suggest the existence of $[L(SO_4)(n\text{-}Bu_4N)]^-$ species in the gaseous state. The peak at *m*/*z* 981.2 can be attributed to the 1 : 1 sulfate complex of the receptor **L** whereas the base peak at *m*/*z* 884.0 in the spectrum can be assigned to the deprotonated receptor and a peak at *m*/*z* 920.6 can be attributed to the chloride complex of **L**. The existence of an ion-pair like $L(SO_4)(n\text{-}Bu_4N)^-$ in the gaseous state is evidence of the strong association of **L** and $(n\text{-}Bu_4N)_2SO_4$.

2-Dimensional diffusion ordered spectroscopy (2D-DOSY) has become an important technique for studying the self-assembly of supramolecular systems in solution.[13] Fig. 3 depicts the DOSY spectra of **1** in DMSO-d_6 at 298 and 333 K. It is evident from the spectra (Fig. 3A) that all the peaks correlated to the



Scheme 1 Synthesis of the receptor, **L**.

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† Electronic supplementary information (ESI) available: Experimental details. CCDC 777533. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c0cc02509g

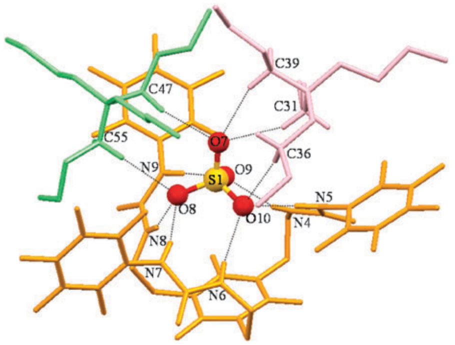

Fig. 1 Binding of SO_4^{2-} with **L** and tetrabutylammonium groups. Non acidic hydrogen atoms and lattice DMF are omitted for clarity.

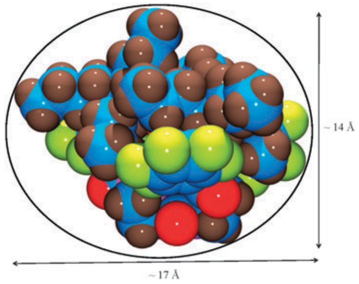

Fig. 2 Space filling model of complex **1**. Lattice DMF is omitted for clarity. Major axis: C62–H62B···H46B–C46 ≈ 17 Å; minor axis C42–H42A···H22A–C22 ≈ 14 Å. Blue: carbon, brown: hydrogen, green: fluorine and red: oxygen.

signals in the chemical shift dimensions are in a horizontal line. Thus both sets of signals attributed to **L** and n-Bu_4N^+ cation have the same diffusion coefficients. Further, the downfield shifted signals of urea –NH resonances ($-NH_c$ and $-NH_d$) are supposed to represent the encapsulated SO_4^{2-} which has the same diffusion coefficient as **L** and n-Bu_4N^+ ions. This supports the fact that **L** and $(n\text{-}Bu_4N)_2SO_4$ exist as a contact ion-pair in solution. Addition of $(n\text{-}Bu_4N)_2SO_4$ to the solution of **L** in DMSO-d_6 showed a DOSY spectrum similar to that of **1** whereas the addition of n-Bu_4N^+ salts of $H_2PO_4^-$, CH_3COO^- or Cl^- to the DMSO-d_6 solution of **L** showed two different sets of peaks with different diffusion coefficients,† representing that these anions do not assist the formation of contact ion-pairs. However, downfield shifted signals of urea –NH resonances are observed due to anion binding to **L**. The hydrodynamic radii (r_s) calculated from the Stokes–Einstein relation, using experimentally obtained diffusion coefficients for **L**, $(n\text{-}Bu_4N)_2SO_4$, **L** + n-$Bu_4NH_2PO_4$, **L** + n-Bu_4NCH_3COO, **L** + n-Bu_4NNO_3, **L** + n-Bu_4NCl and **1** at different temperatures, are tabulated in Table 1. It is evident that **1** represents maximum hydrodynamic radii of 15.39 Å, indicating the bigger size of the aggregated species compared to **L** (12.45 Å) or $(n\text{-}Bu_4N)_2SO_4$ (10.22 Å) or anion bound **L**. The hydrodynamic radii obtained from diffusion measurements for **1** is in good agreement with the average of the dimensions (15.5 Å) calculated from single crystal X-ray analysis in the solid state (Fig. 2). A similar comparison has recently been made in the literature.[14] Variable temperature DOSY experiments of **1** clearly show that the hydrodynamic radius of **1** is sensitive to temperature (Fig. 3B, Table 1). Variable temperature experiments were performed at 298 K, 313 K and 333 K respectively in DMSO-d_6. With the increase in temperature the diffusion coefficient increases along with the development of two different sets of signals which might be attributed to [**L** + SO_4^{2-}] and n-Bu_4N^+ as separated ions at higher temperatures in the solution. Notably, the one-dimensional ^{1}H-NMR spectra do not display any variations in the chemical shifts of urea –NH resonances and do not show broadening of the resonance signals upon changing the temperature, indicating that the sulfate ion remains intact in the cleft even at the elevated temperatures. When the temperature of the solution is cooled down to 298 K, the DOSY spectrum exactly matches with the spectrum of the associated ion-pair, **1**. This indeed justifies the temperature dependent reversible ion-pairing and

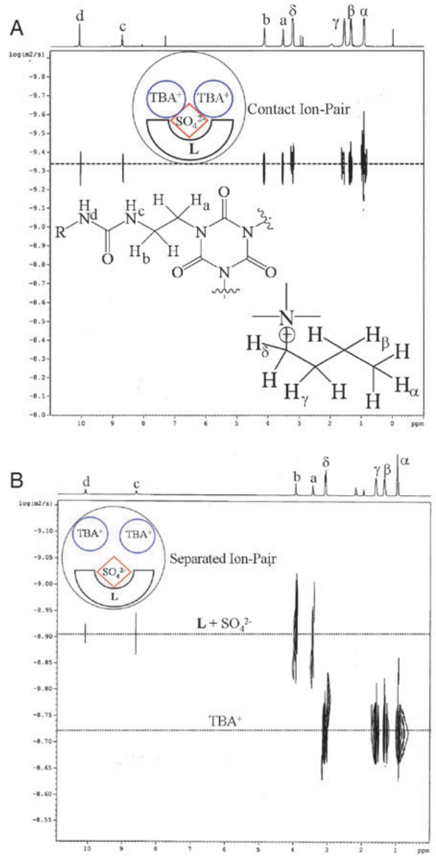

Fig. 3 ^{1}H-DOSY (500 MHz) spectra of complex **1** in DMSO-d_6 at (A) 298 K and (B) 333 K.

Table 1 Diffusion coefficient, D and hydrodynamic radii, r_s in DMSO-d_6 at different temperatures

System	T/K	$D/10^{-10}$ m^2 s^{-1}	r_s/Å
$(n\text{-}Bu_4N^+)_2SO_4^{2-}$	298	10.72 ± 0.02	10.22 ± 0.02
L	298	8.805 ± 0.01	12.45 ± 0.01
Complex **1**	298	7.127 ± 0.01	15.39 ± 0.01
	313	7.752 ± 0.01	14.14 ± 0.01
	333	7.858 ± 0.02	13.95 ± 0.02
L + n-$Bu_4N^+H_2PO_4^-$	298	8.112 ± 0.01	13.52 ± 0.01
L + n-$Bu_4N^+CH_3COO^-$	298	8.258 ± 0.01	13.28 ± 0.01
L + n-$Bu_4N^+NO_3^-$	298	8.521 ± 0.01	12.87 ± 0.01
L + n-$Bu_4N^+Cl^-$	298	8.289 ± 0.01	13.23 ± 0.01

Hydrodynamic radii are calculated from the experimentally obtained diffusion coefficients using the Stokes–Einstein equation.

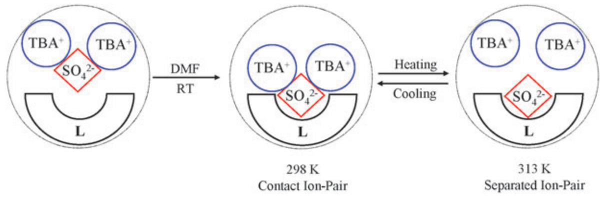

Fig. 4 Proposed modes of ion-pair association and dissociation of **L** and tetrabutylammonium sulfate.

dissociation of **L** and $(n\text{-}Bu_4N)_2SO_4$ in the solution state as shown in Fig. 4.

Detailed binding properties of **L** with different anions in the solution state were also investigated by ^1H NMR experiments in DMSO-d_6 in the presence of various anions as their $n\text{-}Bu_4N^+X^-$ salts (where $X^- = F^-, Cl^-, Br^-, I^-, H_2PO_4^-, HSO_4^-, ClO_4^-, NO_3^-$ and CH_3COO^-).† Substantial changes in chemical shifts are observed for the urea protons ($-NH_c$ and $-NH_d$) of **L** with Cl^-, $H_2PO_4^-$, HSO_4^- and CH_3COO^-, indicating the participation of –NH protons in the solution state binding events. To evaluate the binding of these anions with **L**, ^1H-NMR titrations were carried out in DMSO-d_6. The titration curve showed the best fit for a 1 : 1 binding model for host to guest, in agreement with Job's plots,† and the association constants were calculated using WINEQNMR 2.0 for these anions.[15] The association constants are summarized in Table 2. The stability constants and change in free energy data show that **L** binds very strongly toward SO_4^{2-} compared with other anions with log K of 5.74 M^{-1}. However $H_2PO_4^-$ also displays a significant binding with **L** whereas the binding constant of **L** with CH_3COO^- and Cl^- is comparable. Thus, the binding order of different anions toward **L** is $SO_4^{2-} \gg H_2PO_4^- > CH_3COO^- > Cl^-$. Higher binding affinity in the case of SO_4^{2-} compared to $H_2PO_4^-$ could be due to the existence of ion-pair interaction, without loss of electrostatic energy arising from charge separation in the former case.

Table 2 Binding constants and free energy change of **L** with different anions in DMSO-d_6 at 298 K (errors <5%)

	SO_4^{2-}	$H_2PO_4^-$	CH_3COO^-	Cl^-
log K/M^{-1}	5.74	4.39	3.41	3.38
ΔG/kcal mol^{-1}	−7.82	−5.98	−4.65	−4.61

In conclusion, we have unambiguously demonstrated that encapsulated sulfate selectively assists ion-pair formation with the aliphatic chain of Bu_4N^+ cation *via* strong C–H···O interactions by single crystal X-ray structural analysis. Both ^1H-NMR and DOSY NMR support the recognition of $(n\text{-}Bu_4N)_2SO_4$ in a polar solvent like DMSO. Variable temperature DOSY experiments show the reversible assembly/dis-assembly of the $n\text{-}Bu_4N^+$ sulfate assisted cap. The cyanuric acid platform and the pentafluorophenyl units in the pendant arms of the receptor might have played a crucial role toward sulfate selective/assisted formation of contact ion-pair recognized assembly.

PG thanks the Department of Science and Technology (DST) for financial support through a Swarnajayanti Fellowship. The single crystal X-ray structure analysis of complex **1** was performed in the DST funded National Single Crystal X-ray Facility at IACS.

Notes and references

‡ Crystallographic data for **1**: $C_{65}H_{97}F_{15}N_{12}O_{11}S$, M = 1539.61, monoclinic, space group Cc, a = 32.4(12), b = 12.936(5), c = 23.066(15) Å, β = 126.879(8)°, V = 7733.0(6) Å^3, D_c = 1.322 g cm^{-3}, Z = 4, λ = 0.71073 Å, T = 100(2) K, 25 676 reflections, 12 215 independent (R_{int} = 0.0773), and 9835 observed reflections [$I > 2\sigma(I)$], 971 refined parameters, R = 0.0545, wR_2 = 0.1468. CCDC number: 777533.

1 (*a*) B. D. Smith, in *Ion Pair Recognition by Ditopic Receptors, Macrocyclic Chemistry: Current Trends and Future*, ed. K. Gloe and B. Antonioli, Kluwer, London, 2005, pp. 137–152; (*b*) P. D. Beer and P. A. Gale, *Angew. Chem., Int. Ed.*, 2001, **40**, 486.

2 (*a*) A. P. Davis, D. N. Sheppard and B. D. Smith, *Chem. Soc. Rev.*, 2007, **36**, 348; (*b*) A. L. Sisson, M. R. Shah, S. Bhosale and S. Matile, *Chem. Soc. Rev.*, 2006, **35**, 1269; (*c*) G. W. Gokel, W. M. Leevy and M. E. Weber, *Chem. Rev.*, 2004, **104**, 2723.

3 (*a*) S. K. Kim, J. L. Sessler, D. E. Gross, C. Lee, J. S. Kim, V. M. Lynch, L. H. Delmau and B. J. Hay, *J. Am. Chem. Soc.*, 2010, **132**, 5827; (*b*) M. P. Wintergerst, T. G. Levitskaia, B. A. Moyer, J. L. Sessler and L. H. Delmau, *J. Am. Chem. Soc.*, 2008, **130**, 4129; (*c*) M. Cametti, M. Nissinen, A. D. Cort, L. Mandolini and K. Rissanen, *J. Am. Chem. Soc.*, 2007, **129**, 3641; (*d*) R. Custelcean, L. H. Delmau, B. A. Moyer, J. L. Sessler, W.-S. Cho, D. Gross, G. W. Bates, S. J. Brooks, M. E. Light and P. A. Gale, *Angew. Chem., Int. Ed.*, 2005, **44**, 2537; (*e*) J. M. Mahoney, K. A. Stucker, H. Jiang, I. Carmichael, N. R. Brinkmann, A. M. Beatty, B. C. Noll and B. D. Smith, *J. Am. Chem. Soc.*, 2005, **127**, 2922; (*f*) A. Mele, P. Metrangolo, H. Neukirch, T. Pilati and G. Resnati, *J. Am. Chem. Soc.*, 2005, **127**, 14972.

4 L. O. Abouderbala, W. J. Belcher, M. G. Boutelle, P. J. Cragg, J. W. Steed, D. R. Turner and K. J. Wallace, *Proc. Natl. Acad. Sci. U. S. A.*, 2002, **99**, 5001.

5 (*a*) S. S. Zhu, H. Staats, K. Brandhorst, J. Grunenberg, F. Gruppi, E. Dalcanale, A. Lützen, K. Rissanen and C. A. Schalley, *Angew. Chem., Int. Ed.*, 2008, **47**, 788; (*b*) H. Maeda and Y. Kusunose, *Chem.–Eur. J.*, 2005, **11**, 5661; (*c*) C. A. Ilioudis, D. A. Tocher and J. W. Steed, *J. Am. Chem. Soc.*, 2004, **126**, 12395.

6 (*a*) R. Custelcean, A. Bock and B. A. Moyer, *J. Am. Chem. Soc.*, 2010, **132**, 7177; (*b*) I. Ravikumar, P. S. Lakshminarayanan, M. Arunachalam, E. Suresh and P. Ghosh, *Dalton Trans.*, 2009, 4160; (*c*) R. Custelcean, P. Remy, P. V. Bonnesen, D. Jiang and B. A. Moyer, *Angew. Chem., Int. Ed.*, 2008, **47**, 1866; (*d*) B. Wu, J. Liang, J. Yang, C. Jia, X.-J. Yang, H. Zhang, N. Tang and C. Janiak, *Chem. Commun.*, 2008, 1762; (*e*) A. D. Jose, D. K. Kumar, B. Ganguly and A. Das, *Inorg. Chem.*, 2007, **46**, 5817; (*f*) R. Custelcean, B. A. Moyer and B. P. Hay, *Chem. Commun.*, 2005, 5971.

7 (*a*) Z. Rodriguez-Docampo, S. I. Pascu, S. Kubik and S. Otto, *J. Am. Chem. Soc.*, 2006, **128**, 11206; (*b*) M. A. Hossain, J. M. Llinares, D. Powell and K. Bowman-James, *Inorg. Chem.*, 2001, **40**, 2936.

8 (*a*) S. O. Kang, V. W. Day and K. Bowman-James, *Org. Lett.*, 2008, **10**, 2677; (*b*) S. O. Kang, M. A. Hossain, D. Powell and K. Bowman-James, *Chem. Commun.*, 2005, 328.

9 (*a*) N. N. Adarsh, D. K. Kumar and P. Dastidsar, *CrystEngComm*, 2009, **11**, 796; (*b*) R. Custelcean and P. Remy, *Cryst. Growth Des.*, 2009, **9**, 1985; (*c*) C. R. Bondy, P. A. Gale and S. J. Loeb, *J. Am. Chem. Soc.*, 2004, **126**, 5030.

10 K. A. Mullen and P. D. Beer, *Chem. Soc. Rev.*, 2009, **38**, 1701.

11 F. Hettche and R. W. Hoffmann, *New J. Chem.*, 2003, **27**, 172.

12 K. Bowman-James, *Acc. Chem. Res.*, 2005, **38**, 671.

13 (*a*) Y. Cohen, L. Avram and L. Frish, *Angew. Chem., Int. Ed.*, 2005, **44**, 520; (*b*) J. Rebek, Jr., *Angew. Chem., Int. Ed.*, 2005, **44**, 2068.

14 N. Giuseppone, J.-L. Schmitt, L. Allouche and J.-M. Lehn, *Angew. Chem., Int. Ed.*, 2008, **47**, 2235.

15 M. J. Hynes, *J. Chem. Soc., Dalton Trans.*, 1993, 311.