Crown ethers as pre-organised *exo*-receptors in the divergent recognition of α,ω-diiodoperfluoroalkanes†

Walter Navarrini,[a] Pierangelo Metrangolo,*[b] Tullio Pilati[c] and Giuseppe Resnati*[b]

[a] *Ausimont, Research and Development, 50, via S. Pietzo, I-20021 Bollate, Italy*
[b] *Dipartimento di Chimica, Politecnico di Milano, 7, via Mancinelli, I-20131 Milano, Italy. E-mail: Resnati@dept.chem.polimi.it; Fax: +39 02 2399 3080; Phone: +39 02 2399 3032*
[c] *C.N.R.-Centro Studio Relazioni Struttura Reattività Chimica, Università degli Studi, 19, via Golgi, I-20133 Milano, Italy*

Received (in Cambridge, UK) 21st March 2000, Accepted 11th July 2000
First published as an Advance Article on the web 19th September 2000

Both the nitrogen atoms of Kryptofix® 2.2. **1** act as electron-donors to the iodine atoms of α,ω-diiodoperfluoroalkanes **2a**,**b** giving rise to infinite 1D chains **3a**,**b** as white crystalline solids which are stable in air at room temperature. The structural features of these non-covalent co-polymers have been studied using various techniques (IR, ^{1}H NMR, ^{19}F NMR, X-ray diffraction) and it has been established that when Kryptofix® 2.2. is halogen bonded to iodides **2**, it adopts the same conformation as when in the pure form, namely the *exo–exo* topology. The co-existence of halogen-bonding and hydrogen-bonding in supramolecular architectures **3** suggests pre-organisation of the interacting partners as a new strategy in the rational design of divergent self-assembly processes.

Crown ethers and cryptands are widely employed in research and industry owing to their ability to form remarkably stable inclusion complexes with various metal cations.[1] In these complexes the macrocycle invariably adopts a conformation in which the electron lone pairs of the donor sites are inwardly oriented thus tailoring the molecules to act as *endo*-receptors.[2]

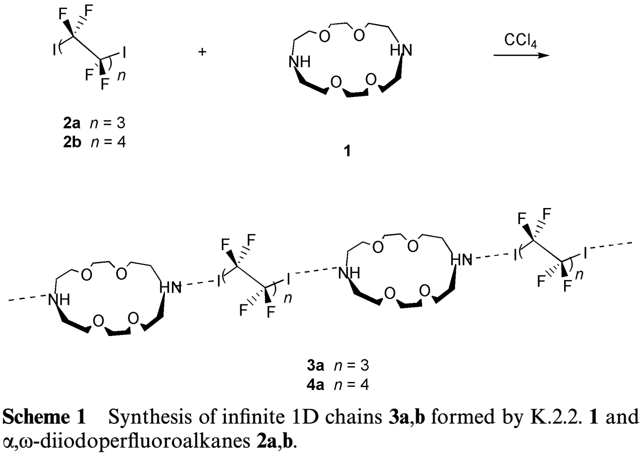
Both the nitrogen lone pairs of 1,4,10,13-tetraoxa-7,16-diazacyclooctadecane **1** (Kryptofix® 2.2., K.2.2.) are outwardly oriented[3] in the preferred conformation of the pure compound (*exo–exo* conformation), and here we exploit this orientation showing how K.2.2 **1** acts as a particularly effective *exo*-receptor when interacting with α,ω-diiodoperfluoroalkanes **2a**,**b**. An attractive intermolecular recognition occurs between **1**, as an electron-donor module, and **2a**,**b**, as electron acceptor modules, both in solution and in the solid state. A single crystal X-ray analysis of co-crystal **3b**, revealed the structural details of the one-dimensional infinite chains formed (Scheme 1).

We have already reported in preliminary communications,[4] how the nitrogen atoms of tertiary amines and pyridine moieties effectively act as electron donors to the iodine atoms of iodoperfluoroalkanes. This non-covalent interaction has been denoted halogen bonding[5] which can be regarded as akin to hydrogen bonding.[6]

In solution, the nitrogen atoms of K.2.2. **1** behave in a similar way as in the solid state as revealed by the chemical shift differences between the ^{19}F and ^{1}H NMR spectra of co-crystals **3a**,**b**, and those of pure precursors **1** and **2a**,**b**. In ^{19}F NMR spectra of concentrated chloroform solutions of co-crystals **3a**,**b**, the difluoromethylene group geminal to iodine is shifted upfield compared to pure modules **2a**,**b**, thus indicating the formation of N···I halogen bonds.[7] On diluting these samples, the chemical shift of the CF_2I group moves back to the frequencies shown by pure iodides **2** and ^{1}H and ^{19}F NMR spectra of highly diluted solutions of co-crystals **3a**,**b** cannot be distinguished from those of pure precursors **1** and **2a**,**b**. On evaporating the solvent, crystalline **3a**,**b** are re-formed. These observations indicate that, on dissolution, non-covalent copolymers **3a**,**b** give rise to the starting free modules **1** and **2** which form dimeric, trimeric, *etc*., adducts through association equilibria which are rapid on the NMR time scale. Also the internal difluoromethylene groups of co-crystals **3a**,**b** are shifted upfield compared to pure **2a**,**b**. Shifts decrease with increasing distance from the iodine atoms, consistent with the specificity of the N···I halogen bonding and its role in determining the observed changes in NMR properties.

It is particularly interesting to observe that solutions of infinite networks **3a**,**b** show distinctly larger shifts in ^{19}F NMR spectra than equimolar solutions of analogous infinite networks **5a**,**b** formed by K.2.2.2. **4** (4,7,13,16,21,24-hexaoxa-1,10-diazabicyclo[8.8.8]hexacosane, Kryptofix® 2.2.2.) with α,ω-diiodoperfluoroalkanes **2a**,**b** (Scheme 2).

Indeed, K.2.2. **1**, preferentially adopting an *exo–exo* conformation, is preorganized[8] for *exo*-recognition processes and is thus more effective than K.2.2.2. **4** in binding diiodoperfluoroalkanes **2a**,**b** *via divergent* assembling processes. Conversely,

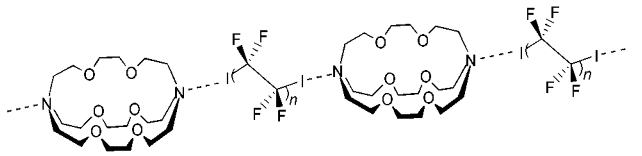


Scheme 1 Synthesis of infinite 1D chains **3a**,**b** formed by K.2.2. **1** and α,ω-diiodoperfluoroalkanes **2a**,**b**.

---

† Perfluorocarbon-hydrocarbon self-assembly Part XI; for Part X see ref. 6.

DOI: 10.1039/b002247k



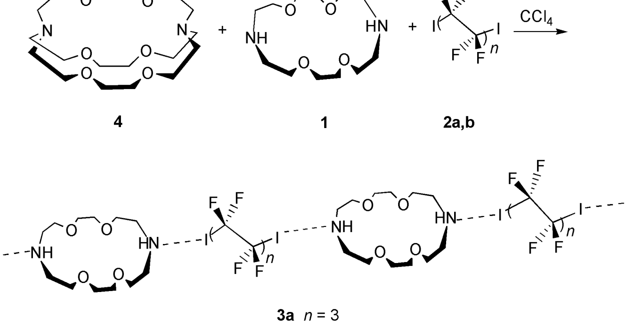
5a $n = 3$
5b $n = 4$

Scheme 2 Infinite 1D chains **5a,b** formed by K.2.2.2. **4** and α,ω-diiodoperfluoroalkanes **2a,b**.

K.2.2.2, generally adopts an *endo–endo* conformation where both nitrogen lone pairs are inwardly oriented. It is therefore ideally pre-organised for *endo*-recognition processes and in fact it shows a greater ability than K.2.2. to form dimeric inclusion adducts when involved in spherical recognition of metal cations.[9] The N···I halogen bonding is however strong enough[10] to change the K.2.2.2. conformation into the less favoured *exo–exo* conformation required for its involvement in divergent self-assembly processes.[11] However, the energetic cost of this conformational induced fit disfavours dimer and trimer adduct formation in solution and results in the smaller ^{19}F NMR shifts discussed above. In order to confirm this behaviour in solution and to measure the different ability of K.2.2. **1** and K.2.2.2. **4** to behave as electron donors in the *exo*-intermolecular recognition of α,ω-diiodoperfluoroalkanes **2**, a competition experiment was devised. Equimolar amounts of crown **1** and cryptand **4** were dissolved in carbon tetrachloride in a vial of clear borosilicate glass. The obtained system was added to a clear carbon tetrachloride solution containing an equimolar amount of 1,6-diiodoperfluorohexane **2a** and the open vial was placed in a sealed cylindrical wide-mouth bottle containing vaseline oil. The solvent was allowed to diffuse and after one day at room temperature, colourless crystals were deposited from the solution. Microanalyses, IR and NMR spectra (^{1}H and ^{19}F) revealed that the crystals were pure adduct **3a**, while the cryptand **4** remained in solution. To establish the generality of these results, the same experiment was performed starting from 1,8-diiodoperfluorooctane **2b**, with pure co-crystal **3b** being exclusively obtained (Scheme 3).

K.2.2. **1** is thus proven to be more effective than K.2.2.2. **4** in driving the divergent self-assembly of α,ω-diiodoperfluoroalkanes **2**.

The thermal characterisation by DSC of infinite networks **3** and **5** gives qualitative indications of their crystal cohesion which are consistent with the electron-donor ability of modules **1** and **4**. Melting endotherms of pure components **1**, **2a,b** and **4** are absent in the heating curves of co-crystals **3a,b** and **5a,b** which show a single endotherm, indicating the formation of a new crystal species containing the two components.[12] Interestingly, the adducts **3a,b** obtained starting from K.2.2., which is better tailored to divergent recognition processes, melt at temperatures higher than **5a,b** obtained from K.2.2.2.



3a $n = 3$
3b $n = 4$

Scheme 3 Selective recognition in solution of α,ω-diiodoperfluoroalkanes **2a,b** by K.2.2. **1** in the presence of K.2.2.2. **4**.

Also some spectral properties of donor module **1** are affected by the N···I halogen bonding interactions with α,ω-diiodoperfluoroalkanes **2**, both in solution and in the solid state. For instance, in the ^{1}H NMR spectra of infinite chains **3a,b** the N–H signals undergo line-narrowing and downfield shifts compared to pure **1**. This is consistent with stronger intramolecular hydrogen bonds in **3a,b** to the ether oxygens than in pure precursor **1**, as expected from the diminished electron density on the amine hydrogen atoms caused by electron donation from nitrogen to iodine.

In the solid state, the halogen-bonding between hydrocarbon and perfluorocarbon modules markedly affects the vibrational spectra of pure compounds **1** and **2a,b**. Similar to what is observed on formation of other donor–acceptor adducts,[12,13] the C–H and C–F stretching modes in the 2700–3000 and 1100–1250 cm^{-1} region, respectively, occur at higher and lower wavenumbers in networks **3** than in pure precursors **1** and **2**. Once again, consistent with stronger hydrogen bonding, the N–H stretching moves to lower wavenumber and shows greater intensity in co-crystals **3**.

The single crystal X-ray analysis of infinite network **3b** reveals the structure of its supramolecular architecture (Fig. 1).

The crown ether and the perfluorooctane modules **1** and **2b**, respectively, segregate into layers parallel to (100) and are held together exclusively by N···I halogen bonding. This segregation is a consequence of the low affinity typically existing between perfluorocarbon and hydrocarbon derivatives.[14] Indeed, K.2.2. is sparingly soluble in *n*-perfluorohexane and -octane, but becomes soluble when 1-iodoperfluorohexane and -octane are added. The N···I bond distance is 2.861(4) Å, this value being similar to those observed in analogous infinite chains formed by diiodoperfluorocarbons and dinitrogen substituted hydrocarbons[4] and shorter than the sum of the van

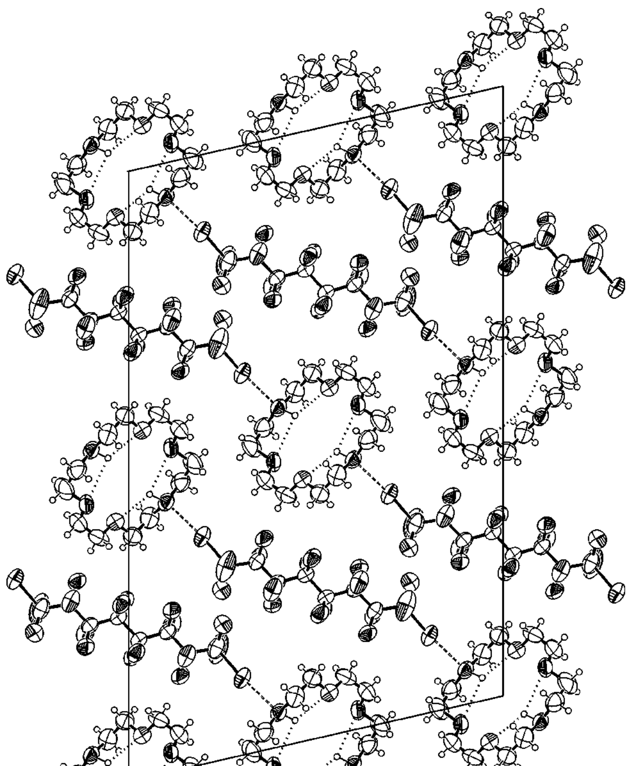


Fig. 1 ORTEP-III projection of co-crystal **3b** along the *b* axis. Selected bond lengths (Å) and angles (°): C–I 2.185(5); N···I 2.861(4), C–I···N 173.85(17). Dotted lines indicate 1,5-intramolecular bifurcated hydrogen bonds and dashed lines intermolecular halogen bonds. Only the more populated position of the O2 atom is shown.

der Waals radii of N (1.55 Å) and I (1.98 Å),[15] but longer than the average N–I covalent bond (2.07 Å).[16] Similar to other analogous infinite networks,[4] the intermolecular interaction in **3b** leads to a lengthening of the C–I bond [C–I···N angle 173.85(17)°].

In co-crystal **3b**, the perfluorooctyl chain of the diiodide module **2b** deviates from the exact *trans*-planar conformation [the torsion angles along the chain I–C7–C8–C9–C10–C10(1 − x, −y, 1 − z) are in the sequence: −173.4(3), −168.4(4), −163.3(2)°], probably to minimise the intramolecular fluorine repulsion between 1,3-positioned difluoromethylene groups. While recent exceptions have been reported,[17] similar behaviour has been frequently observed in long[18] and short[19] perfluoroalkyl chains. In co-crystal **3b**, the crown modules **1** adopt an *exo–exo* conformation closely corresponding with that found in the homocrystal of **1**.[3] This conformation is quite probably favoured by the weak but significant bifurcated 1,5-intramolecular hydrogen bond[20] involving the amine hydrogen and the two nearby oxygen atoms of the polyoxomethylene chains [N···O1 2.864(5) Å, N···O2 2.868(6) Å] (Fig. 1). Being intramolecular, however, this interaction suffers severe conformational restraints, which are probably responsible for its deviation from linearity (mean value of O···H–N *ca.* 103(5)°] (Fig. 1). The lone pairs of the tetrahedral nitrogens are thus outwardly oriented, ideally *pre-organised* for *divergent* supramolecular chemistry. This contrasts with the behaviour of K2.2.2. **4** which shows in its homocrystal a clear preference for the *endo–endo* conformation targeted to the convergent recognition approach. In co-crystal **3b** the K.2.2. modules form nanotubes which develop along the *b* cell axis. The crown ether least square planes are 3.897(3) Å from each other and form an angle of 44.4(4)° with the nanotube axis.

In conclusion, the results described here show that K.2.2. **1** is more effective than K.2.2.2. **4** in recognising diiodoperfluoroalkanes **2**. While the pursuit of module pre-organization[8,9] targeted to effective *endo* recognition processes has led from acyclic to macrocyclic and macropolycyclic ligands, the pursuit of module pre-organisation towards effective *exo* recognition processes is at an early stage, with more efficient structures and principles for their rational design still to be identified. Here, it is shown how *pre-organisation* of the electron donor module **1** in an *exo–exo* conformation through intramolecular hydrogen bonding results in particularly effective *exo*-recognition processes with acceptors **2** through intermolecular halogen-bonding formation. The general effectiveness of this strategy in *divergent* supramolecular chemistry is under active investigation.

Experimental

All materials were obtained from commercial suppliers and were used without further purification. ^{19}F NMR spectra were recorded with a Bruker AV 500 spectrometer. ^{1}H NMR spectra were recorded with a Bruker ARX 400 spectrometer. The IR spectra were recorded with a Perkin-Elmer 2000 FT-IR spectrophotometer. DSC analyses were obtained on a DSC 820 Mettler heat flux calorimeter (silver furnace, ceramic sensor with 14 Au–AuPd thermocouples).

General procedure for the synthesis of infinite chains 3

Co-crystals **3a**,**b** were obtained by dissolving at room temperature in a vial of clear borosilicate glass, equimolar amounts of Kryptofix® 2.2. **1** and α,ω-diiodoperfluoroalkanes **2a**,**b** using carbon tetrachloride as solvent. The open vial was placed within a sealed cylindrical wide-mouth bottle containing vaseline oil, and volatiles were allowed to diffuse at room temperature. After 1 day, white crystals were isolated, filtered off, and washed with cold carbon tetrachloride.

Co-crystal 3a. Anal. Found (calc. for $C_{18}H_{26}N_2O_4I_2F_{12}$): C, 26.22 (26.48); H, 3.37 (3.21); N, 3.51 (3.43); I, 30.86 (31.09)%; mp (carbon tetrachloride) 112–118 °C (decomp.). FTIR (KBr pellets, cm^{-1}) 3312, 2903, 2875, 1192, 1162, 1150, 1110, 986, 591. ^{19}F NMR (CDCl$_3$, 305 K): $\Delta\delta_F = \delta_{\text{pure } \mathbf{2a}} - \delta_{\mathbf{3a}}$ (0.05 M), $\Delta\delta(\mathrm{IC}F_2\mathrm{CF}_2\mathrm{CF}_2\text{–}) = 0.71$, $\Delta\delta(\mathrm{ICF}_2\text{-}\mathrm{C}F_2\mathrm{CF}_2\text{–}) = 0.07$, $\Delta\delta(\mathrm{ICF}_2\mathrm{CF}_2\mathrm{C}F_2\text{–}) = 0.02$; $\Delta\delta_F = \delta_{\text{pure } \mathbf{2a}} - \delta_{\mathbf{3a}}$ (0.07 M), $\Delta\delta(\mathrm{IC}F_2\mathrm{CF}_2\mathrm{CF}_2\text{–}) = 1.05$, $\Delta\delta(\mathrm{ICF}_2\text{-}\mathrm{C}F_2\mathrm{CF}_2\text{–}) = 0.11$, $\Delta\delta(\mathrm{ICF}_2\mathrm{CF}_2\mathrm{C}F_2\text{–}) = 0.06$. ^{1}H NMR (CDCl$_3$, 305 K): δ 2.05 (br s, NH, 2 H).

Co-crystal 3b. Anal. Found (calc. for $C_{20}H_{26}N_2O_4I_2F_{16}$): C, 25.89 (26.22); H, 3.08 (2.86); N, 3.21 (3.06); I, 28.00 (27.70)%; mp (carbon tetrachloride) 103–110 °C (decomp.). FT IR (KBr pellets, cm^{-1}) 3313, 2909, 2877, 1199, 1105, 628, 547. ^{19}F NMR (CDCl$_3$, 305 K): $\Delta\delta_F = \delta_{\text{pure } \mathbf{2b}} - \delta_{\mathbf{3b}}$ (0.05 M): $\Delta\delta(\mathrm{IC}F_2\mathrm{CF}_2\mathrm{CF}_2\mathrm{CF}_2\text{–}) = 0.74$, $\Delta\delta(\mathrm{ICF}_2\mathrm{C}F_2\mathrm{CF}_2\mathrm{CF}_2\text{–}) = 0.10$, $\Delta\delta(\mathrm{ICF}_2\mathrm{CF}_2\mathrm{C}F_2\mathrm{CF}_2\text{–}) = 0.04$, $\Delta\delta(\mathrm{ICF}_2\mathrm{CF}_2\mathrm{CF}_2\mathrm{C}F_2\text{–}) = 0.03$; $\Delta\delta_F = \delta_{\text{pure } \mathbf{2b}} - \delta_{\mathbf{3b}}$ (0.06 M): $\Delta\delta(\mathrm{IC}F_2\mathrm{CF}_2\mathrm{CF}_2\mathrm{CF}_2\text{–}) = 1.05$, $\Delta\delta(\mathrm{ICF}_2\mathrm{C}F_2\mathrm{CF}_2\mathrm{CF}_2\text{–}) = 0.13$, $\Delta\delta(\mathrm{ICF}_2\mathrm{CF}_2\mathrm{C}F_2\mathrm{CF}_2\text{–}) = 0.08$, $\Delta\delta(\mathrm{ICF}_2\mathrm{CF}_2\mathrm{CF}_2\mathrm{C}F_2\text{–}) = 0.06$. ^{1}H NMR (CDCl$_3$, 305 K): δ 2.10 (br s, NH, 2 H).

Crystal data for $C_{12}H_{26}N_2O_4 \cdot C_8F_{16}I_2$ 3b

$M = 916.23$, monoclinic, space group $I2/a$, $a = 31.1690(13)$, $b = 5.4620(2)$, $c = 19.6270(8)$ Å, $\beta = 102.81°$, $U = 3258.2(2)$ Å^3, Mo-Kα radiation: ($\lambda = 0.710\,73$ Å, $Z = 4$, $T = 291$ K, μ(Mo-Kα) = 2.050 mm^{-1}. 14 323 absorption corrected reflections (multiscan, $T_{\min} = 1.000$, $T_{\max} = 0.589$), 3687 unique ($R_{\text{int}} = 0.0253$). Structure solution by SIR92[21] and refinement on F^2 by SHELX97[22] program packages. Anisotropic displacement parameters (ADPs) for all heavy atoms; only one H atom bonded to N was refined, all others being placed in calculated positions. The oxygen atom O2 was disordered and split over two positions refined with occupancies of *ca.* 3/4 and 1/4. Similarity restraints on distances and on ADPs were imposed for the C3C4O2C5C6 and C3C4O2′C5C6 chains. At final convergence $R_1 = 0.0572$, $wR_2 = 0.1242$, $S = 1.060$ for 210 parameters, 46 restraints and all reflections using the following weighting scheme: $w = 1/[\sigma^2(F_o^2) + (0.0664P)^2 + 2.7203P]$, $P = (F_o^2 + 2F_c^2)/3$. Difference electronic density ranges between −0.43 and 1.46 e Å^{-3}, the maximum residue being located at 0.92 Å from I atoms.

CCDC reference number 440/194. See http://www.rsc.org/suppdata/nj/b0/b002247k for crystallographic files in .cif format.

Acknowledgements

Financial support from the European Union (COST-D12 Action, Fluorous Media: A Tool for Environmentally Compatible Processes) and MURST (Co-finanziamento '99) are gratefully acknowledged.

References

1 S. R. Cooper, *Crown Compounds; Towards Future Applications*, VCH, New York, 1992; G. W. Gokel, *Crown Ethers and Cryptands*, RSC, Cambridge, 1991.

2 F. Mathieu and R. Weiss, *J. Chem. Soc., Chem. Commun.*, 1973, 816; M. Herceg, B. Metz, D. Moras and R. Weiss, *Bull. Soc. Chim. Fr.*, 1972, **2**, 551.

3 M. Herceg and R. Weiss, *Bull. Soc. Chim. Fr.*, 1972, **2**, 549.

4 V. Amico, S. V. Meille, E. Corradi, M. T. Messina and G. Resnati, *J. Am. Chem. Soc.*, 1998, **120**, 8261; S. V. Meille, E. Corradi, M. T. Messina, P. Metrangolo and G. Resnati, *Tetrahedron Lett.*, 1999, **40**, 7519; A. Manfredi, M. T. Messina, P. Metrangolo, T. Pilati, S. Quici and G. Resnati, *Supramol. Chem.*, submitted.

5 J. M. Dumas, L. Gomel and M. Guerin, in *The Chemistry of Functional Groups, Supplement D*, ed. S. Patai and Z. Rappoport,

John Wiley and Sons, New York, 1983, p. 985; J. P. M. Lommerse, A. J. Stone, R. Taylor and F. H. Allen, *J. Am. Chem. Soc.*, 1996, **118**, 3108; A. C. Legon, *Chem. Eur. J.*, 1998, **4**, 1890; A. C. Legon, *Angew. Chem., Int. Ed.*, 1999, **38**, 2687.

6 E. Corradi, S. V. Meille, M. T. Messina, P. Metrangolo and G. Resnati, *Angew. Chem., Int. Ed.*, 2000, **39**, 1782.

7 M. T. Messina, P. Metrangolo, S. Pappalardo, M. F. Parisi, T. Pilati and G. Resnati, *Chem. Eur. J.*, 2000, in press.

8 J. M. Lehn, *Angew. Chem., Int. Ed. Engl.*, 1988, **27**, 89; J. M. Lehn, *Supramolecular Chemistry: Concepts and Perspectives*, VCH, Weinheim, 1995.

9 A. P. Marchand, A. S. Mc Kim and K. A. Kumar, *Tetrahedron*, 1998, **54**, 13421.

10 D. W. Larsen and A. L. Allred, *J. Phys. Chem.*, 1965, **69**, 2400; S. V. Meille, P. Metrangolo, G. Raos, G. Resnati and G. Valerio, *J. Phys. Chem. A*, 2000, **104**, 1617.

11 L. R. MacGillivray and J. L. Atwood, *Chem. Commun.*, 1997, 477; R. Foster, in *Organic Charge-Transfer Complexes*, Academic Press, London, 1969, p. 100.

12 A. Lunghi, P. Cardillo, M. T. Messina, P. Metrangolo, W. Panzeri and G. Resnati, *J. Fluorine Chem.*, 1998, **91**, 191.

13 M. T. Messina, P. Metrangolo and G. Resnati, in *Asymmetric Fluoroorganic Chemistry: Synthesis, Applications and Future Directions*, ACS Symp. Ser. no. 746, ed. P. V. Ramachandran, American Chemical Society, Washington DC, 1999, ch. 17; M. T. Messina, P. Metrangolo, W. Navarrini, S. Radice, G. Resnati and G. Zerbi, *J. Mol. Struct.*, 2000, **524**, 87.

14 B. E. Smart, in *Organofluorine Chemistry: Principles and Commercial Applications*, ed. R. E. Banks, B. E. Smart and J. C. Tatlow, Plenum Press, New York, 1994.

15 A. Bondi, *J. Phys. Chem.*, 1964, **68**, 441.

16 K. Padmanabhan, I. E. Paul and D. Y. Curtin, *Acta Crystallogr., Sect. C*, 1990, **46**, 88.

17 D. D. Desmarteau, W. T. Pennington and L. X. Xue, *Angew. Chem., Int. Ed.*, 1999, **38**, 2687.

18 C. W. Bunn and E. S. Howells, *Nature*, 1954, **174**, 549.

19 D. A. Dixon, *J. Phys. Chem.*, 1992, **96**, 3968;T. Caronna, E. Corradi, S. V. Meille, B. Novo and G. Resnati, *J. Fluorine Chem.*, 1999, **97**, 103.

20 F. H. Allen, C. A. Baalham, J. P. M. Lommerse, P. R. Raithby and E. Sparr, *Acta Crystallogr., Sect. B*, 1997, **53**, 1017.

21 A. Altomare, G. Cascarano, C. Giacovazzo, A. Guagliardi, M. C. Burla, G. Polidori and M. Camalli, *J. Appl. Crystallogr.*, 1994, **27**, 435.

22 G. M. Sheldrick, SHELX97, Program for the Refinement of Crystal Structures, University of Göttingen, Germany, 1997.