Clathrates with mixed guests

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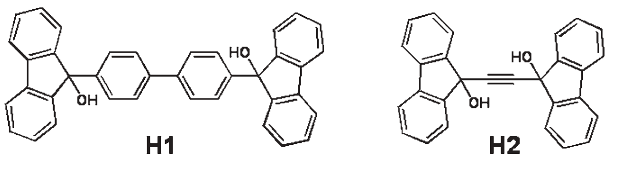
Investigation of the selectivities of two diol organic hosts for pairs of small organic guests gave interesting results which could be correlated with the crystal structures of the inclusion compounds containing mixtures of the two guests; these structures were compared with those of the single guest inclusion compounds.

The field of inclusion compounds with mixed guests is well established[1,2] and is an important one as systematic studies can establish what aspects are important in the selection of different guests, such as steric factors, guest symmetry, solubility and polarity. The possibility of controlling the ratio of mixed guests in a host–guest system has implications for crystal engineering[3] and a knowledge of the physical and chemical properties has significance in fields such as chemical sensors and optical and electronic properties of organic crystals.[4,5]

The possibility of selective enclathration by a host can be investigated by carrying out competition experiments and many systems have been studied using this method.[6–9]

This study is comprised of two separate investigations and in the first investigation the selectivity of the host 9,9′-(biphenyl-4,4′-diyl)difluoren-9-ol (**H1**)[10] for a pair of guests with very similar chemical compositions but significantly different boiling points was examined. The second investigation involved a pair of guests with very similar boiling points and which form inclusion compounds with a particular host which have different host : guest ratios when crystallised at different temperatures. We thus investigated the selectivity of the host 9,9′-(ethyne-1,2-diyl)difluoren-9-ol (**H2**)[10] for these guests and carried out the competition experiments at two different temperatures in order to see whether the selectivity would change with changing temperature. The structural formulas of the host compounds are shown in Scheme 1.

In the first investigation the host **H1** was found to form inclusion compounds with tetrahydrofuran (**H1**·2THF) and diethyl ether (**H1**·2Et$_2$O) and the selectivity of this host for THF *versus* Et$_2$O was investigated. Thermal gravimetry, TG, was employed to analyse the stoichiometries of the two inclusion compounds, and the structures of **H1**·2THF and **H1**·2Et$_2$O were elucidated by single crystal X-ray diffraction methods at low temperature.†



Scheme 1

The **H1**·2THF structure crystallises in the space group $P2_1/c$, with $Z = 4$, and with the asymmetric unit consisting of one host and two guest molecules. The host molecules pack to form restricted channels along [001] in which the guest molecules are located and the crystal packing viewed down [001] is shown in Fig. 1. The structure is stabilised by two (Host)–O–H···O(Guest) hydrogen bonds.

H1·2Et$_2$O also crystallises in the space group $P2_1/c$, with $Z = 4$, but the cell dimensions are different from those of **H1**·2THF with the *a*-axis being half the length and the *b*-axis double the length. However, the packing of the structure is similar to that of **H1**·2THF with the host molecules packing to form the same channels along [001] in which the guest molecules are located. The structure is also stabilised by the same hydrogen bonding pattern.

Competition experiments were carried out in order to determine whether the host would selectively include either of the guests. Such competition experiments, in which inclusion compounds are grown from solutions of pairs of guests of varying mole fractions, typically give rise to one of the selectivity curves depicted in Fig. 2.

The results of the competition experiments carried out with THF and Et$_2$O are displayed in Fig. 3, with the diagonal line representing zero selectivity. From these results it can be seen that the host **H1** shows a preference for THF over the whole concentration range.

Although many such experiments have been carried out, the structures corresponding to the crystals derived from the mixed guest solution have not been previously analysed.

The structures of the inclusion compounds formed from three of the solutions with mixed guests were elucidated and the H : G ratios obtained from the crystal structures were found to correlate with the mole fractions obtained from the competition experiments.

The solution with $X_{THF} = 0.55$ gave crystals with $Z_{GC} = 0.73$ and refinement of the crystal structure yielded **H1**·1.35(1)THF·0.65(1)Et$_2$O, which corresponds to $Z = 0.68$.

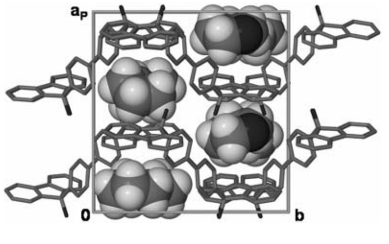


Fig. 1 Packing diagram of **H1**·2THF viewed along [001] with guest molecules represented with van der Waals radii.

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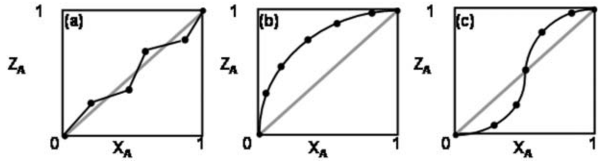

Fig. 2 Typical selectivity curves obtained from competition experiments. Each graph shows the mole fraction X of one of the guests in the initial solution *versus* the mole fraction Z of the same guest included in the crystal, displaying (a) poor selectivity, (b) good selectivity and (c) concentration dependent selectivity.

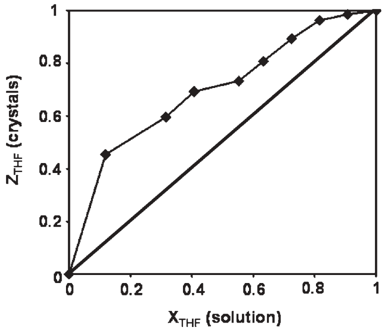

Fig. 3 Results of the THF *versus* Et_2O competition experiments, in which THF is preferentially enclathrated over the whole concentration range.

Similarly the solution with X_{THF} = 0.32 gave crystals with Z_{GC} = 0.60 and crystal structure refinement yielded **H1**·1.15(1)THF·0.85(1)Et_2O, which corresponds to Z = 0.58. The solution with X_{THF} = 0.12 gave Z_{GC} = 0.45 and crystal structure refinement yielded **H1**·0.90(1)THF·1.10(1)Et_2O, which corresponds to Z = 0.45.†

These compounds all crystallise in the space group $P2_1/c$ and are all isostructural to **H1**·2THF. In each case the H : G_{TOTAL} = 2 with one whole molecule on one of the guest sites and two partial molecules superimposed on the other guest site. The changes which occur in the positions of the guest molecules are summarised in Fig. 4.

In the second investigation the host **H2** was found to form inclusion compounds with ethanol (1.5**H2**·2EtOH and **H2**·2EtOH) and acetonitrile (**H2**·MeCN·H_2O and **H2**·2MeCN). Inclusion compounds 1.5**H2**·2EtOH and **H2**·MeCN·H_2O were formed by crystallisation at 25 °C, while inclusion compounds **H2**·2EtOH and **H2**·2MeCN were formed by crystallisation at −26 °C. Thermal gravimetry, TG, was employed to analyse the stoichiometries of the four inclusion compounds, and the structures were elucidated by single crystal X-ray diffraction methods at low temperature.† The crystal structures of **H2**·2EtOH and **H2**·2MeCN will not be discussed further.

The **H2**·MeCN·H_2O structure crystallises in the space group $P2_1/c$ with Z = 8 and the host molecules pack to form restricted undulating channels along [001] in which the guest molecules are located. The crystal packing viewed along [010] is displayed in Fig. 5(a).

The 1.5**H2**·2EtOH structure crystallises in the space group $P\bar{1}$ with Z = 2. The host molecules pack to form rows of cavities along [010] with each cavity containing four guest molecules and the crystal packing viewed along [100] is shown in Fig. 5(b).

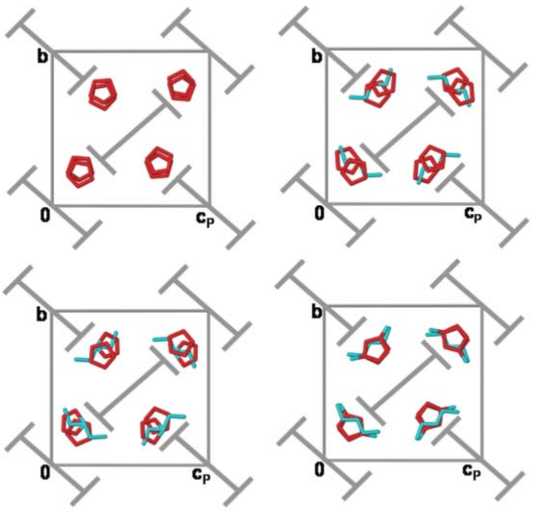

Fig. 4 Schematic diagram summarising the differences between the four structures with the THF guests shown in red and the Et_2O guests shown in blue.

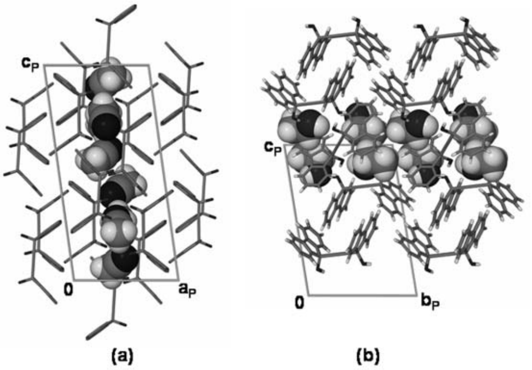

Fig. 5 Packing diagram of (a) **H2**·MeCN·H_2O viewed along [010] and (b) 1.5**H2**·2EtOH viewed along [100] with guest molecules represented with van der Waals radii.

Competition experiments were carried out at both 25 °C and at −26 °C to determine whether the host shows any selectivity for the two guests. The results of these competition experiments are illustrated in Fig. 6 with the diagonal line representing zero selectivity, the grey dots representing the results obtained at 25 °C and the black diamonds representing the results obtained at −26 °C.

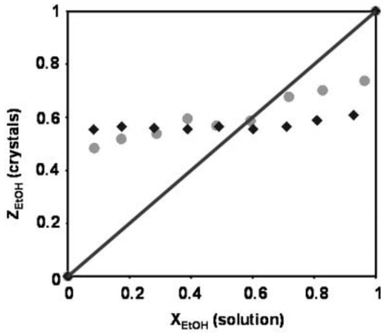

Fig. 6 Results of the EtOH *versus* MeCN competition experiments, with unusually invariant mole fractions of EtOH included in the crystals.

Of the many systems that we have used to study selectivity of bulky organic hosts with pairs of volatile guests, all the results correspond to one of the typical selectivity profiles shown in Fig. 2(a), (b) or (c), but in this case a very different result, which illustrates a unique type of molecular recognition, was found.

It is clear that these results do not give rise to any of the typical selectivity curves, but rather display a very interesting and unusual pattern.

At −26 °C, given any ratio of the two guests, the host forms an inclusion compound with $Z_{EtOH} = 0.56$. At room temperature, although the same compound is not formed in each case, only a small range of mole fractions are obtained, varying between $Z_{EtOH} \sim 0.5$ and $Z_{EtOH} \sim 0.7$, with Z_{EtOH} increasing slightly with X_{EtOH}.

Refinement of the crystal structures of the compounds formed at 25 °C from solutions with $X_{EtOH} = 0.10$, $X_{EtOH} = 0.60$ and $X_{EtOH} = 0.89$ yielded 1.5**H2**·EtOH·MeCN (corresponding to $Z = 0.5$), 1.5**H2**·1.07(1)EtOH·0.93(1)MeCN (corresponding to $Z = 0.53$) and 1.5**H2**·1.41(1)EtOH·0.59(1)MeCN (corresponding to $Z = 0.70$) respectively.† The crystal structures can thus be correlated with the mole fractions obtained from the competition experiments. All three structures crystallise in the space group $P\bar{1}$ with $H : G_{TOTAL} = 1.5 : 2$ and are isostructural to 1.5**H2**·2EtOH in terms of packing of the host molecules. The crystal packing of 1.5**H2**·EtOH·MeCN viewed along [100] is illustrated in Fig. 7 as an example.

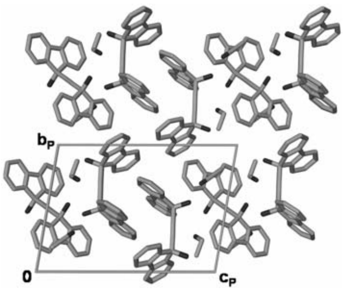

Fig. 7 Packing diagram of 1.5**H2**·EtOH·MeCN viewed along [100].

The cell dimensions of the compounds formed at −26 °C were determined and it was found that in each case the cell dimensions were the same as those of 1.5**H2**·2EtOH, the inclusion compound formed with EtOH at 25 °C. This is an extremely interesting result as, despite the fact that the host forms different inclusion compounds with either EtOH or MeCN when crystallised at −26 °C, when given any mixture of the two at −26 °C, it always forms the same structure as the 25 °C EtOH structure.

Clathrate compounds are an important aspect of supramolecular chemistry[11] and this study displays some novel results showing interesting selectivity profiles, and more importantly giving new insight into clathrates with mixed guests through crystal structure analysis, which in each case could be correlated with the selectivity profiles.

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Notes and references

† *Crystal data* for **H1**·2THF: $C_{38}H_{26}O_2 \cdot 2(C_4H_8O)$, $M = 658.80$, monoclinic, $P2_1/c$, $a = 15.8094(5)$, $b = 14.9432(4)$, $c = 15.5776(4)$ Å, $\beta = 103.219(1)°$, $V = 3582.6(2)$ Å^3, $Z = 4$, $T = 113$ K, $\mu = 0.077$ mm^{-1}, 20794 reflections measured, 7625 unique ($R_{int} = 0.0686$), final R index [$I > 2(I)$]: $R_1 = 0.0495$.

Crystal data for **H1**·2Et$_2$O: $C_{38}H_{26}O_2 \cdot 2(C_4H_{10}O)$, $M = 658.80$, monoclinic, $P2_1/c$, $a = 7.5658(2)$, $b = 32.1197(8)$, $c = 15.3726(5)$ Å, $\beta = 99.269(1)°$, $V = 3686.9(2)$ Å^3, $Z = 4$, $T = 113$ K, $\mu = 0.075$ mm^{-1}, 13168 reflections measured, 7260 unique ($R_{int} = 0.1205$), final R index [$I > 2(I)$]: $R_1 = 0.0646$.

Crystal data for **H1**·1.35THF·0.65Et$_2$O: $C_{38}H_{26}O_2 \cdot 1.35(C_4H_8O) \cdot 0.65(C_4H_{10}O)$, $M = 660.81$, monoclinic, $P2_1/c$, $a = 15.1601(6)$, $b = 15.2878(6)$, $c = 15.7069(7)$ Å, $\beta = 101.288(2)°$, $V = 3569.9(3)$ Å^3, $Z = 4$, $T = 113$ K, $\mu = 0.077$ mm^{-1}, 14223 reflections measured, 7653 unique ($R_{int} = 0.0510$), final R index [$I > 2(I)$]: $R_1 = 0.0690$.

Crystal data for **H1**·1.15THF·0.85Et$_2$O: $C_{38}H_{26}O_2 \cdot 1.15(C_4H_8O) \cdot 0.85(C_4H_{10}O)$, $M = 660.81$, monoclinic, $P2_1/c$, $a = 15.1157(3)$, $b = 15.2709(4)$, $c = 15.7497(4)$ Å, $\beta = 100.986(1)°$, $V = 3568.9(2)$ Å^3, $Z = 4$, $T = 113$ K, $\mu = 0.077$ mm^{-1}, 14794 reflections measured, 7794 unique ($R_{int} = 0.0537$), final R index [$I > 2(I)$]: $R_1 = 0.0518$.

Crystal data for **H1**·0.9THF·1.1Et$_2$O: $C_{38}H_{26}O_2 \cdot 0.9(C_4H_8O) \cdot 1.1(C_4H_{10}O)$, $M = 660.81$, monoclinic, $P2_1/c$, $a = 15.0708(5)$, $b = 15.2736(5)$, $c = 15.8003(5)$ Å, $\beta = 100.415(1)°$, $V = 3577.1(2)$ Å^3, $Z = 4$, $T = 113$ K, $\mu = 0.077$ mm^{-1}, 13596 reflections measured, 7458 unique ($R_{int} = 0.0588$), final R index [$I > 2(I)$]: $R_1 = 0.0657$.

Crystal data for **H2**·MeCN·H$_2$O: $C_{28}H_{18}O_2 \cdot C_2H_3N \cdot H_2O$, $M = 447.51$, monoclinic, $P2_1/c$, $a = 11.1764(2)$, $b = 18.3251(3)$, $c = 23.1848(5)$ Å, $\beta = 97.8852(7)°$, $V = 4703.6(2)$ Å^3, $Z = 8$, $T = 113$ K, $\mu = 0.081$ mm^{-1}, 17961 reflections measured, 10473 unique ($R_{int} = 0.0478$), final R index [$I > 2(I)$]: $R_1 = 0.0575$.

Crystal data for 1.5**H2**·2EtOH: $1.5(C_{28}H_{18}O_2) \cdot 2(C_2H_6O)$, $M = 671.77$, triclinic, $P\bar{1}$, $a = 9.5245(1)$, $b = 11.5340(2)$, $c = 16.2754(3)$ Å, $\alpha = 99.2001(5)$, $\beta = 91.6087(6)$, $\gamma = 90.1904(9)°$, $V = 1764.19(5)$ Å^3, $Z = 2$, $T = 113$ K, $\mu = 0.081$ mm^{-1}, 14087 reflections measured, 7628 unique ($R_{int} = 0.0230$), final R index [$I > 2(I)$]: $R_1 = 0.0409$.

Crystal data for 1.5**H2**·EtOH·MeCN: $1.5(C_{28}H_{18}O_2) \cdot C_2H_6O \cdot C_2H_3N$, $M = 666.76$, triclinic, $P\bar{1}$, $a = 9.7084(2)$, $b = 11.5615(2)$, $c = 16.0451(4)$ Å, $\alpha = 80.2148(7)$, $\beta = 87.4110(7)$, $\gamma = 89.337(1)°$, $V = 1772.93(7)$ Å^3, $Z = 2$, $T = 113$ K, $\mu = 0.079$ mm^{-1}, 15234 reflections measured, 8256 unique ($R_{int} = 0.0310$), final R index [$I > 2(I)$]: $R_1 = 0.0415$.

Crystal data for 1.5**H2**·1.07EtOH·0.93MeCN: $1.5(C_{28}H_{18}O_2) \cdot 1.07C_2H_6O \cdot 0.93C_2H_3N$, $M = 666.76$, triclinic, $P\bar{1}$, $a = 9.6894(1)$, $b = 11.5580(2)$, $c = 16.0629(3)$ Å, $\alpha = 80.2875(8)$, $\beta = 87.5278(7)$, $\gamma = 89.419(1)°$, $V = 1771.44$ (5) Å^3, $Z = 2$, $T = 113$ K, $\mu = 0.079$ mm^{-1}, 14887 reflections measured, 8142 unique ($R_{int} = 0.0361$), final R index [$I > 2(I)$]: $R_1 = 0.0452$.

Crystal data for 1.5**H2**·1.41EtOH·0.59MeCN: $1.5(C_{28}H_{18}O_2) \cdot 1.41C_2H_6O \cdot 0.59C_2H_3N$, $M = 666.76$, triclinic, $P\bar{1}$, $a = 9.6310(2)$, $b = 11.5476(2)$, $c = 16.1540(3)$ Å, $\alpha = 80.5393(9)$, $\beta = 87.788(1)$, $\gamma = 89.6587(8)°$, $V = 1770.81(6)$ Å^3, $Z = 2$, $T = 113$ K, $\mu = 0.079$ mm^{-1}, 14997 reflections measured, 8198 unique ($R_{int} = 0.0329$), final R index [$I > 2(I)$]: $R_1 = 0.0468$.

CCDC 632726–632735. For crystallographic data in CIF or other electronic format see DOI: 10.1039/b618782j

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