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Inclusion of quinolines by binaphthol: structures and selectivity

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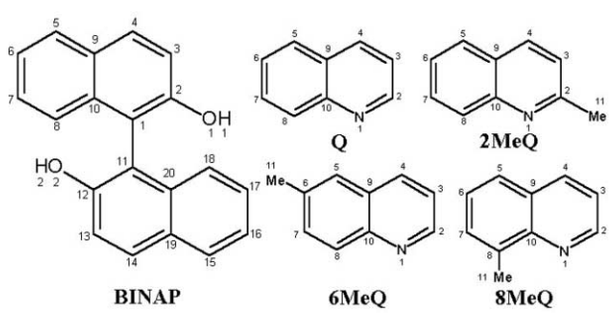
The enclathration selectivity of the host compound 2,2′-dihydroxyl-1,1′-binaphthyl, BINAP, towards the guests quinoline (Q), 2-methylquinoline (2MeQ), 6-methylquinoline (6MeQ) and 8-methylquinoline (8MeQ) were established by competition experiments as: BINAP·2(2MeQ) > BINAP·2Q > BINAP·2(8MeQ) > BINAP·2.5(6MeQ). The crystal structures of the inclusion compounds were elucidated and are all stabilised by (host)-O–H ··· N(guest) hydrogen bonds. Thermal analysis yields the same sequence with respect to the relative stabilities. pH Control was employed to dramatically modify the selectivity profile of the pair of 2-methylquinoline (2MeQ) and 8-methylquinoline (8MeQ).

Introduction

The process of separation by enclathration is well established, and is attractive because it may be employed to separate liquids with similar boiling points, when distillation may be impractical or the target molecules are heat sensitive and liable to decompose at the distillation temperature. The procedure has the advantage of being simple, economic, and can be designed to be highly efficient. This method of separation has been employed using cholic acid as the host to discriminate between nitrobenzene and aniline,[1] as well as a series of mono-substituted benzenes.[2] *N*,*N*′-Ditritylurea and its analogues have been employed to enclathrate selectively a variety of guests,[3] while the binding of volatile guests by a *p-tert*-butylcalix[4]arene has been demonstrated.[4] When one wants to exercise a measure of control on the selectivity of a particular system, the approach has been to alter the host compound. This has been shown to be successful in the case of ion selectivity by crown ethers,[5] or by changing the chirality of certain substituents on amide hosts derived from mandelic acid.[6]

The host 2,2′-dihydroxyl-1,1′-binaphthyl, **BINAP**, forms inclusion compounds with a range of guests, and its selectivity towards mixtures of acetone–tetrahydrofuran and morpholine–dioxane has been measured.[7] It has been employed to separate isomers of xylidine,[8] lutidine[9] and picoline.[10]

We now present the results of the structural analyses and guest competition experiments of **BINAP** with quinoline (**Q**), 2-methylquinoline (**2MeQ**), 6-methylquinoline (**6MeQ**) and 8-methylquinoline (**8MeQ**), as well as the effect of pH changes on guest selectivity. The atomic numbering of the inclusion compounds is shown in Scheme 1. The guest atoms are labelled with the suffix 'G'.



Scheme 1

Experimental

Crystals of all the inclusion compounds † were obtained by slow evaporation of solutions of the host dissolved in excess liquid guest. Thermogravimetry (TG) was employed to determine the host : guest ratios. Details of the crystal data, intensity data collection and refinement are given in Table 1. Cell dimensions were established from the intensity data measured on a Nonius Kappa CCD diffractometer using graphite-monochromated Mo-Kα radiation. The strategy for the data collections was evaluated using the COLLECT software.[11] For all structures, data were collected by the standard phi scan and omega scan techniques, and were scaled and reduced using DENZO-SMN[12] software. The structures were solved by direct methods using SHELX-86[13] and refined by full-matrix least-squares with SHELX-97,[14] refining on F^2. The program X-Seed[15] was used as a graphical interface.

For all structures, the non-hydrogen atoms were refined anisotropically except for **BINAP·2.5(6MeQ)**, in which one of the guests is disordered and was treated isotropically. The hydrogens bonded to carbon were refined with geometric constraints and the hydroxyl hydrogens of the host were located in difference electron density maps and refined with simple bond length constraints of d(O–H) = 0.97 Å.

Competition experiments were carried out by setting up a series of 11 vials made up of mixtures such that the mole fraction of the given guest varied from 0 to 1. The host was added to each mixture keeping the ratio of total guest : host at 20 : 1 and dissolved by warming. Crystals were obtained by slow evaporation, were filtered, dried and dissolved in chloroform. These solutions as well as the mother liquors were analysed by gas chromatography.

Thermogravimetry (TG) was carried out on a Mettler Toledo TGA/SDTA851 (Switzerland) and differential scanning calorimetry (DSC) was carried out on the Perkin-Elmer PC 7 Series system. The experiments were performed over a temperature range of 304–504 K at a constant heating rate of 10 °C min^{-1} with a purge of dry nitrogen flowing at 30mL min^{-1}. Samples were filtered and blotted dry on filter paper to remove surface solvent and were placed in an open platinum pan in TG and in a crimped, vented aluminium pan in DSC.

† CCDC reference numbers 224350–224353. See http://www.rsc.org/suppdata/ob/b3/b314691j/ for crystallographic data in.cif or other electronic format.

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Table 1 Crystal structure solution and refinement parameters

Inclusion compounds	**BINAP·2Q**	**BINAP·2(2MeQ)**	**BINAP·2.5(6MeQ)**	**BINAP·2(8MeQ)**
Molecular formula	$C_{20}H_{14}O_2{\cdot}2C_9H_7N_1$	$C_{20}H_{14}O_2{\cdot}2C_{10}H_9N_1$	$C_{20}H_{14}O_2{\cdot}2.5C_{10}H_9N_1$	$C_{20}H_{14}O_2{\cdot}2C_{10}H_9N_1$
M_r/g mol^{-1}	544.62	572.68	644.27	572.68
Crystal system	Monoclinic	Monoclinic	Triclinic	Monoclinic
Space group	*C*2/*c*	*C*2	$P\bar{1}$	*C*2/*c*
a/Å	18.1633(8)	14.8402(3)	8.8396(1)	14.4495(3)
b/Å	11.0249(5)	10.5377(2)	9.4695(1)	11.0481(3)
c/Å	14.0928(8)	9.7304(2)	21.6106(3)	19.6571(6)
α/°	90	90	94.652(1)	90
β/°	97.171(2)	99.443(1)	98.068(1)	105.100(1)
γ/°	90	90	103.822(1)	90
Volume/Å^3	2800.0(2)	1501.04(5)	1726.77(4)	3029.70(14)
Z	4	2	2	4
D_c/g cm^{-3}	1.292	1.267	1.239	1.255
F(000)	1144	604	659	1208
μ/mm^{-1}	0.080	0.078	0.075	0.077
Data collection				
Range scanned, *θ*/°	1.02–27.10	1.02–27.48	1.02–27.48	1.02–27.48
Temperature/K	203	203	203	203
No. of measured reflections	5175	6438	14800	5783
No. of independent reflections	3064	3420	7905	3402
No. of observed reflections	1688	2538	4984	3402
No. of parameters	189	204	434	204
R_{int}	0.0378	0.0242	0.0268	0.0307
Range of indices, *h*, *k*, *l*	±23/−11,14/±17	±19/±13/±12	±11/±12/−28,26	±18/−12,13/±25
Refinement				
Final *R* indices [$F_0 > 4(F_0)$], *R*1	0.0531	0.0378	0.0745	0.0534
w*R*2(F^2)	0.1235	0.0894	0.2028	0.1520
R indices (all data)	0.1264	0.0630	0.1180	0.1110
Goodness of fit on F^2, *S*	1.017	1.037	1.068	1.018
Weighting scheme {where $P = [\max(0, F_0^2) + 2F_c^2]/3$}	$w = (\sigma^2F^2 + (0.0451P)^2 + 0.8610P)^{-1}$	$w = (\sigma^2F^2 + (0.0483P)^2)^{-1}$	$w = (\sigma^2F^2 + (0.0942P)^2 + 1.3822P)^{-1}$	$w = (\sigma^2F^2 + (0.0637P)^2 + 1.3132P)^{-1}$
Max./min. height $\Delta\rho$ in difference electron density map/e Å^{-3}	0.194/−0.224	0.130/−0.153	1.108/−0.519	0.372/−0.160

Results and discussion

Structures

BINAP·2Q. This crystallises in the space group $C2/c$ with $Z = 4$. The host lies on the diad at Wyckoff position *e*, and the quinoline guests are in general positions. The quinolines are hydrogen bonded to the host *via* (host)O–H ··· N(guest) hydrogen bonds with d(O ··· N) = 2.726(2) Å. The quinolines lie in channels running in the [10$\bar{1}$] direction as shown in Fig. 1.

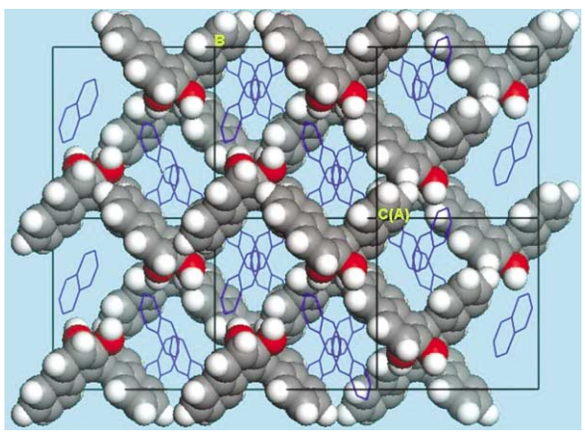

Fig. 1 Space-filling diagram for **BINAP·2Q** viewed down [10$\bar{1}$] showing the channels where the guest **Q** molecules reside. The guest molecules are shown as sticks without hydrogens.

BINAP·2(2MeQ). This crystallises in the space group $C2$ with $Z = 2$. The host lies on the diad at Wyckoff position *a*, with the 2-methylquinoline guest in a general position. The structure is again stabilised by (host)O–H ··· N(guest) hydrogen bonds with d(O ··· N) = 2.739(2) Å. This structure displays a case of spontaneous resolution and this inclusion compound is a conglomerate. This is a relatively open structure with ribbons of host molecules running parallel to [100], as shown in Fig. 2. The guest molecules reside in channels which intersect and which run in the directions [001] and [110].

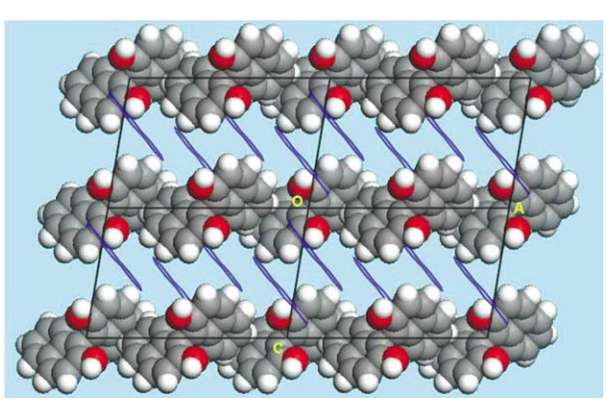

Fig. 2 Space-filling diagram of **BINAP·2(2MeQ)** viewed along [110], showing ribbons of host molecules running in the [100] direction. The guest molecules are shown as sticks without hydrogens.

BINAP·2.5(6MeQ). This crystallises in the space group $P\bar{1}$ with $Z = 2$. One host and two guest molecules are in general positions, and are hydrogen bonded to each other *via* (host)O–H ··· N(guest) with d(O ··· N) = 2.760(3) Å and 2.690(3) Å respectively. Another disordered 6-methylquinoline guest lies on a centre of inversion at Wyckoff position *f*. The refinement of this latter guest was difficult, with some atomic positions shared between the two halves of the disordered molecule, and with all atoms treated isotropically. This guest is not hydrogen bonded to the host. This is also a relatively open structure

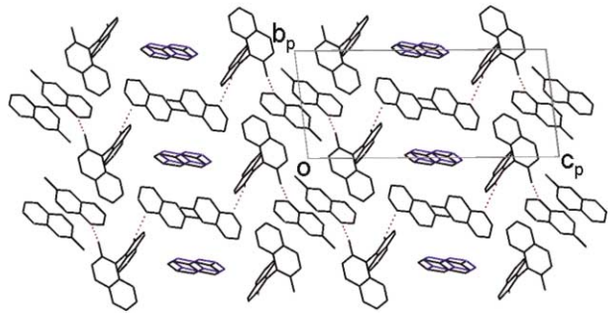

Fig. 3 Projection of **BINAP·2.5(6MeQ)**, viewed along [100]. All hydrogens are omitted. The disordered **6MeQ** molecules are shown in different colours. The hydrogen bonds are shown as dotted lines.

exhibiting layers of host and guest molecules lying perpendicular to the *c* axis. The packing is shown in Fig. 3 as a projection down [100], with hydrogens omitted for clarity.

BINAP·2(8MeQ). This crystallises in the space group $C2/c$ with $Z = 4$. The host lies on the diad at Wyckoff position *e*, and the guest is in a general position. We again have (host)O–H ··· N(guest) hydrogen bonds with d(O ··· N) = 2.833(2) Å. The guest molecules lie in channels running parallel to [100].

Thermal analysis

The DSC results for the four compounds are shown in Fig. 4, taken in the range of 304 K to 504 K. Each compound displays a single endotherm due to guest release with concomitant dissolution of the host. We have recorded the onset temperatures (T_{on}) in Table 2, which also give the value of $T_{on} - T_b$ and T_{on}/T_b for each compound, where T_b is the normal boiling point of the guest in K. We have found that onset temperature, T_{on}, characterising the temperature of guest release, is a reliable measure of thermal stability. For inclusion compounds of a given host with a variety of guests, the onset temperatures are clearly a function of both the host–guest interactions and the intrinsic properties of the guest itself. In particular, the normal boiling point T_b of the guest is important, and a useful measure of the relative stabilities of a series of inclusion compounds are the values of ($T_{on} - T_b$) and T_{on}/T_b.[16] In general two situations arise: (i) when the guest is volatile and gives rise to a separate DSC endotherm for guest release followed by a second endotherm due to the melting of the apohost; and (ii) when

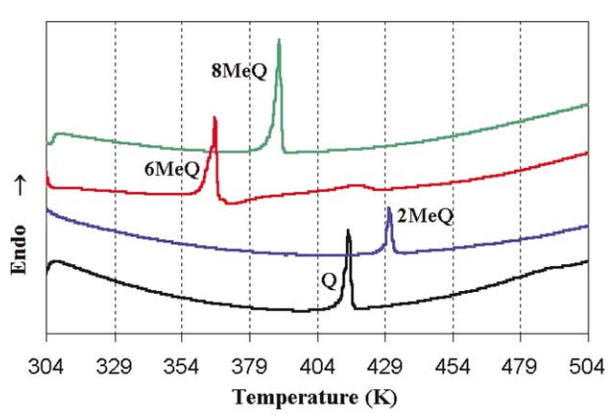

Fig. 4 DSC curves of all four inclusion compounds.

Table 2 DSC results

Guest	b_p/K	T_{on}/K	($T_{on} - T_b$)/K	T_{on}/T_b
Q	507	413	−94	0.80
2MeQ	520	429	−91	0.83
6MeQ	532	364	−168	0.68
8MeQ	521	388	−133	0.74

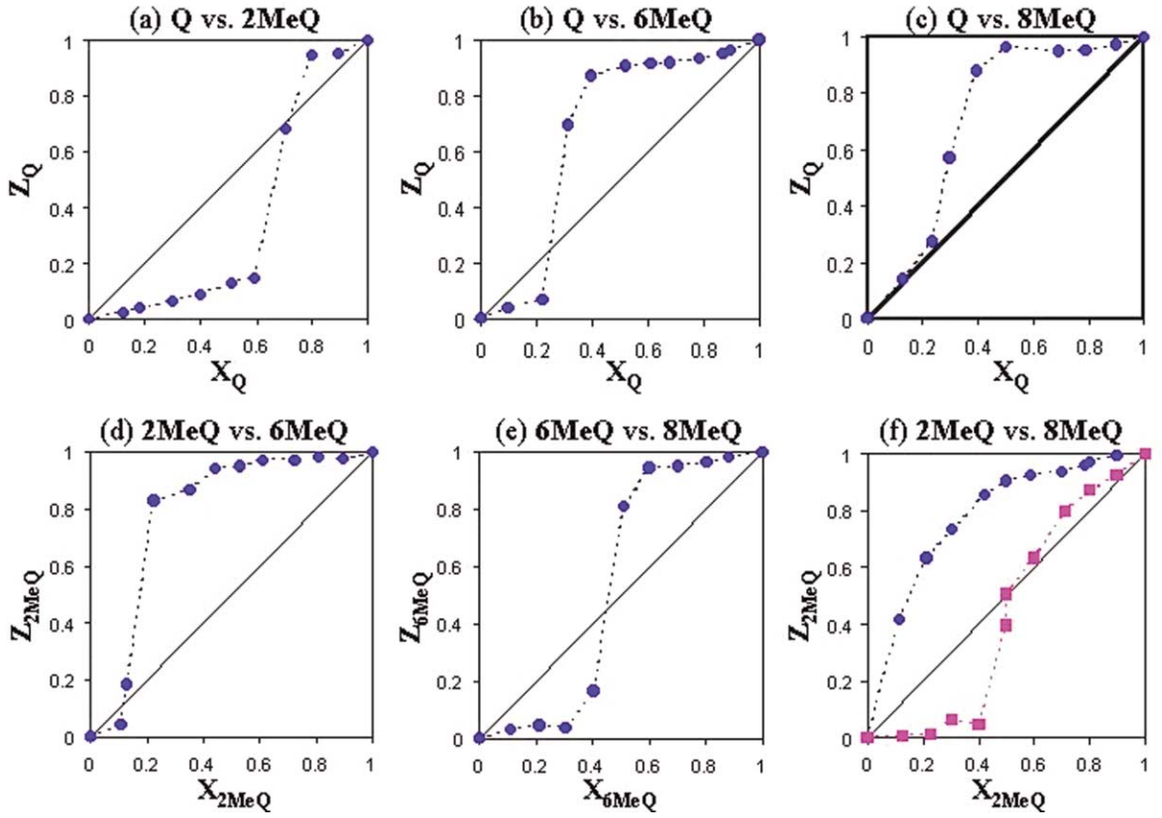

Fig. 5 Competition results.

the guest is a high boiling liquid, which gives rise to a single dissolution endotherm. We note that using these criteria the relative stability of the four inclusion compounds under study follows the sequence **BINAP·2(2MeQ) > BINAP·2Q > BINAP·2(8MeQ) > BINAP·2.5(6MeQ)**

Selectivity

The competition results are shown in Fig. 5. In the **Q** *vs*. **2MeQ** case, Fig. 5a, the selectivity is concentration dependent, with the cross-over point occurring at $X_Q = 0.71$. A similar situation occurs with **Q** *vs*. **6MeQ**, Fig. 5b, with the cross-over point at $X_Q = 0.25$. In Fig. 5c we note that **Q** is favoured over **8MeQ** over the complete range of mixtures. In the case of **2MeQ** *vs*. **6MeQ**, Fig. 5d, the former is largely favoured, while in **6MeQ** *vs*. **8MeQ**, Fig. 5e, the selectivity is again strongly concentration dependent with the cross-over occurring at $X_{6MeQ} = 0.45$.

An interesting result occurred in the **2MeQ** *vs*. **8MeQ** case, shown in Fig. 5f. Here the blue line shows the selectivity curve for the two liquids, showing that **2MeQ** is favoured over **8MeQ** over the complete range. We may define a selectivity coefficient:

$$K_{A:B} = (K_{B:A})^{-1} = Z_A/Z_B * X_B/X_A \; (X_A + X_B = 1)$$

where A and B are the two guests, and X and Z are the mole fractions of the given guest in the liquid mixture and in the crystal respectively.[17] A selectivity coefficient $K_{A:B} = 1$ corresponds to the diagonal line in Fig. 5. In the **2MeQ/8MeQ** competition experiments the selectivity coefficient is 7.7 on average. However, we noted that the pK_b value of **2MeQ** = 8.1 and that of **8MeQ** is 9.0, making **2MeQ** the stronger base. We reasoned therefore that by acidifying this mixture, the **2MeQ** would be preferentially protonated at the N atom ($\Delta pK_b = 0.9$), thus disrupting the host–guest hydrogen bonding and so favouring the enclathration of **8MeQ**. Thus we repeated the competition experiments and acidified the **2MeQ–8MeQ** mixtures with conc. HCl (10.2 mol dm^{-3}), such that H : (**2MeQ**+**8MeQ**) : HCl was 1 : 20 : 10. This resulted in a new selectivity profile shown by the violet line of Fig. 5f, in which **8MeQ** is now strongly favoured up to $X_{2MeQ} = 0.50$, after which the selectivity coefficient was close to 1.

The competition experiment results may be summarised by stating that the selectivity follows the sequence **BINAP·2(2MeQ) > BINAP·2Q > BINAP·2(8MeQ) ≈ BINAP·2.5(6MeQ)**.

Conclusion

The host **BINAP** forms inclusion compounds with quinoline (**Q**), 2-methylquinoline (**2MeQ**), 6-methylquinoline (**6MeQ**) and 8-methylquinoline (**8MeQ**). All these structures are stabilised by (host)O–H ··· N(guest) hydrogen bonds. Competition experiments and DSC yield the same results with respect to the relative stabilities. pH control can be employed to dramatically modify the selectivity profile of a pair of quinoline bases when the difference in pK_a is sufficiently large.

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