

Inclusion compounds of binaphthol with picolines: structures, selectivity and kinetics of desolvation

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The crystal structures of the inclusion compounds formed between the host 2,2'-dihydroxy-1,1'-binaphthyl and the three picoline isomers have been elucidated and their lattice energies calculated. The selectivities of enclathration by the host have been measured by competition experiments. The thermal stabilities and activation energies of desolvation of the compounds have been determined. The kinetics of desolvation are correlated to the structures.

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1. Introduction

Structure elucidation of inclusion compounds is fundamental to the study of molecular recognition. Refined crystal structures allow us to calculate the strengths and directions of the intermolecular forces that act upon a particular host-guest system. These in turn can be correlated to a number of macroscopic properties of the compounds, such as thermal stability, enthalpy of guest release and kinetic parameters of desolvation.

The host, **H** = 2,2'-dihydroxy-1,1'-binaphthyl (binaphthol, BNP) conforms to the principles of directed host design (Weber, 1991) in that it is bulky, rigid and contains hydroxyl moieties which facilitate the formation of coordinatocathrates. This host has been studied extensively and the structures of the non-porous α -phase, the apohosts, have been elucidated for the racemic (Gridunova *et al.*, 1982) and both enantiomerically pure forms (Mori *et al.*, 1993; Toda *et al.*, 1997). The structures of its inclusion compounds with a variety of small guests have been solved. Of particular interest are the structures carried out with the resolved host with a chiral guest such as methyl *m*-tolyl-sulfoxide (Toda *et al.*, 1984), dimethylphenylphosphinate (Toda *et al.*, 1988), ethyl *m*-tolyl selenoxide (Fujiwara *et al.*, 1990), proline (Periasamy *et al.*, 1997), ethylmethyl (*m*-tolyl) amine oxide (Toda *et al.*, 1989) and 1,2-cyclohexane-diamine (Fukushima *et al.*, 1999).

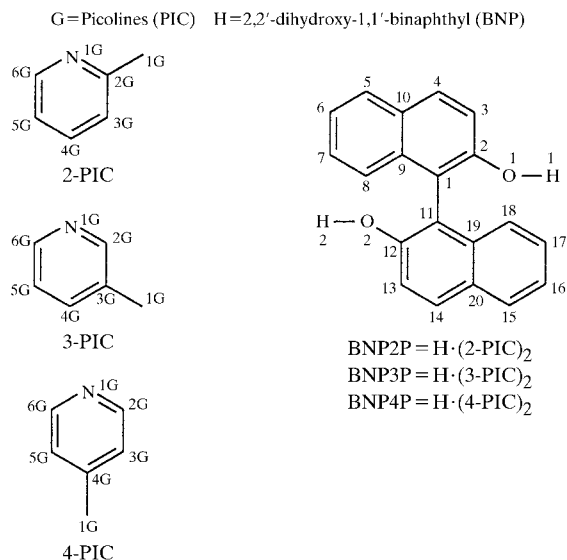
We have also employed this host to form two distinct inclusion compounds with 1,4-dioxane. These compounds had different host:guest ratios and their structures, thermal stabilities and activation energies of desolvation have been measured (Nassimbeni & Su, 2000).

We now present the results of the competition experiments between this host and the three picoline isomers and the selectivity is discussed in terms of the interaction revealed by the crystal structures.

2. Experimental

2.1. Structures

The inclusion compounds were obtained by dissolving the host compound BNP in the liquid picolines and crystals of suitable quality appeared by slow evaporation within a period of 24 h. Preliminary cell dimensions and space-group symmetry were determined photographically and subsequently refined on a Nonius Kappa CCD diffractometer using graphite-monochromated Mo $K\alpha$ radiation. The strategy for the data collections was evaluated using the *COLLECT* software, scaled and reduced with *DENZO-SMN* software (Otwinowski & Minor, 1997). Salient crystal and experimental data are given in Table 1,¹ and the atomic numbering scheme is shown in Scheme I. All three structures were solved by direct methods using *SHELXS86* (Sheldrick, 1985) and refined employing full-matrix least-squares with the program *SHELXL97* (Sheldrick, 1997) refining on F^2 . Packing diagrams were produced using the program *X-seed* (Barbour, 1999).



In all three structures, the H atoms were located in difference electron-density maps. The aromatic H atoms were refined by constrained refinement with isotropic temperature factors assigned as 1.2 times the value of the U_{eq} of their parent atoms. The hydroxyl H atoms on the host were refined with simple bond-length constraints and independent isotropic temperature factors. The methyl groups on the guest, all except one of the two guests in BNP3P, were disordered and refined with two positions of the H atoms.

2.2. Competition experiments

These were carried out between pairs of guests as follows: A series of nine vials was made up with mixtures of two guests such that the mole fraction of a given guest varied from 0 to 1.

¹Supplementary data for this paper are available from the IUCr electronic archives (Reference: AN0579). Services for accessing these data are described at the back of the journal.

The host was added to the mixture and allowed to dissolve by warming. The total guest:host ratio was kept at 20:1 in each case. The solutions were allowed to cool and to evaporate slowly. The resulting crystalline inclusion compounds were filtered, dried and dissolved in chloroform and these, as well as the mother liquors from which the crystals were obtained, were analysed by gas chromatography.

The experiment was extended to analyse simultaneous competition by all three isomers. Initial compositions of three guest mixtures were selected judiciously in order to sample the three guest components that are represented on the equilateral triangle shown in Fig. 3, in which the three apices represent the pure guests. The equal mixture of the guests with

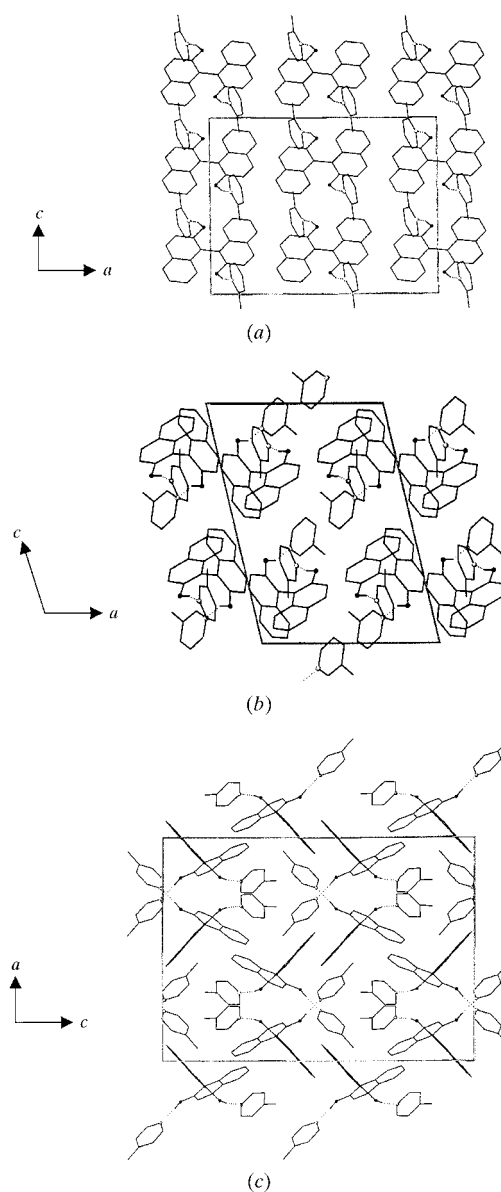


Figure 1 Projection along [010] for (a) BNP2P, (b) BNP3P and (c) BNP4P. The hydrogen bonding is shown as dotted lines. The O atoms on the host are shown as solid balls and the N atoms on the guest as grey balls. All H atoms except the hydroxyl H atoms on the host are omitted.

Table 1

Experimental details.

	BNP2P	BNP3P	BNP4P
Crystal data			
Chemical formula	C ₂₀ H ₁₄ O ₂ ·2C ₆ H ₇ N	C ₂₀ H ₁₄ O ₂ ·2C ₆ H ₇ N	C ₂₀ H ₁₄ O ₂ ·2C ₆ H ₇ N
Chemical formula weight	472.56	472.56	472.56
Cell setting, space group	Monoclinic, <i>C2/c</i>	Monoclinic, <i>P2₁/c</i>	Orthorhombic, <i>Pbca</i>
<i>a</i> , <i>b</i> , <i>c</i> (Å)	18.274 (3), 9.887 (2), 14.021 (2)	12.118 (1), 13.2614 (10), 16.581 (1)	18.119 (3), 10.812 (2), 25.665 (5)
β (°)	90.41 (3)	103.448 (2)	90.000 (1)
<i>V</i> (Å ³)	2533.2 (8)	2591.5 (3)	5027.8 (2)
<i>Z</i>	4	4	8
<i>D_x</i> (Mg m ⁻³)	1.239	1.211	1.249
Radiation type	Mo <i>K</i> α	Mo <i>K</i> α	Mo <i>K</i> α
μ (mm ⁻¹)	0.077	0.076	0.078
Temperature (K)	173 (2)	173 (2)	173 (2)
Crystal size (mm)	0.20 × 0.10 × 0.05	0.37 × 0.1 × 0.1	0.50 × 0.30 × 0.10
Data collection			
No. of measured, independent and observed parameters	4593, 2461, 1727	13 104, 4826, 3380	17 012, 4135, 2669
Criterion for observed reflections	<i>I</i> > 2σ(<i>I</i>)	<i>I</i> > 2σ(<i>I</i>)	<i>I</i> > 2σ(<i>I</i>)
<i>R</i> _{int}	0.0238	0.0342	0.0531
θ _{max} (°)	26.41	26.36	25.40
Range of <i>h</i> , <i>k</i> , <i>l</i>	-22 → <i>h</i> → 21 -12 → <i>k</i> → 0 -17 → <i>l</i> → 17	-14 → <i>h</i> → 15 -16 → <i>k</i> → 16 -16 → <i>l</i> → 19	-20 → <i>h</i> → 19 -9 → <i>k</i> → 11 -26 → <i>l</i> → 28
Refinement			
Refinement on	<i>F</i> ²	<i>F</i> ²	<i>F</i> ²
<i>R</i> [<i>F</i> ² > 2σ(<i>F</i> ²)], <i>wR</i> (<i>F</i> ²), <i>S</i>	0.0415, 0.1105, 1.035	0.041, 0.1055, 1.021	0.043, 0.1122, 1.022
No. of reflections and parameters used in refinement	2461, 165	4826, 335	4135, 335
H-atom treatment	Mixed	Mixed	Mixed
Weighting scheme	$w = 1/[\sigma^2(F_o^2) + (0.0531P)^2 + 0.6410P]$, where $P = (F_o^2 + 2F_c^2)/3$	$w = 1/[\sigma^2(F_o^2) + (0.0463P)^2 + 0.4284P]$, where $P = (F_o^2 + 2F_c^2)/3$	$w = 1/[\sigma^2(F_o^2) + (0.0544P)^2 + 0.5718P]$, where $P = (F_o^2 + 2F_c^2)/3$
(Δ/σ) _{max}	0.001	0.023	0.001
$\Delta\rho$ _{max} , $\Delta\rho$ _{min} (e Å ⁻³)	0.171, -0.173	0.175, -0.152	0.17, -0.166
Extinction method	<i>SHELXL97</i> (Sheldrick, 1997)	<i>SHELXL97</i> (Sheldrick, 1997)	<i>SHELXL97</i> (Sheldrick, 1997)
Extinction coefficient	0.0035 (6)	0.0100 (9)	0.0027 (4)

Computer programs used: *SHELXS86* (Sheldrick, 1985), *SHELXL97* (Sheldrick, 1997).

mole fraction 1/3 each, representing the centre of the triangle, was also analysed. The crystalline inclusion compounds obtained as well as the mother liquors were analysed as before.

2.3. Thermal analysis and kinetics of desolvation

Thermogravimetry (TG) and differential scanning calorimetry (DSC) were carried out on a Perkin–Elmer PC7-Series system. TG analyses were performed to ascertain accurate host:guest ratios, while DSC was used to determine onset temperatures of guest release and to monitor any phase changes occurring in structures upon heating. These experiments were performed over the temperature range 303–503 K at a heating rate of 10 K min⁻¹ with a purge of dry nitrogen flowing at 30 ml min⁻¹. The samples were crushed, blotted dry and placed in open platinum pans for TG experiments and in crimped but vented aluminium pans for DSC. Data for the isothermal kinetics of desolvation were obtained from TG at selected temperatures.

3. Results and discussion

BNP2P crystallized in the space group *C2/c* with four host and eight guest molecules per unit cell. The host molecules were therefore located on a diad at Wyckoff position *e* and the guests in general positions. The guests are located in channels parallel to [101] at *y* = 0.25 and 0.75, with an approximately constant cross-sectional area of 5.5 × 5.5 Å². The structure is stabilized by host···guest hydrogen bonds with (host)O—H···N(guest) having O···N distances of 2.697 (2) Å. Details of the hydrogen bonding for all three structures are given in Table 2. A projection of the structure, viewed along [010] is shown in Fig. 1(*a*).

BNP3P crystallized in *P2₁/c* with *Z* = 4 and both host and guest molecules are in general positions. The guest molecules are located in channels that run along [010], with a cross-sectional area of 5 × 6 Å² approximately. The guests are hydrogen bonded to the host, with O···N distances of 2.708 (2) and 2.779 (2) Å. The packing is shown in Fig. 1(*b*).

BNP4P crystallized in the space group *Pbca*, with *Z* = 8. The host and guest molecules are again in general positions. The

Table 2
Hydrogen bonding details.

		$D-H \cdots A$ (Å)	$H \cdots A$ (Å)	$D \cdots A$ (Å)	$D-H \cdots A$ (°)
BNP2P	O1–H1···N1G	0.98 (3)	1.769 (5)	2.697 (2)	156 (2)
BNP3P	O1–H1···N1GB ⁱ	0.97 (1)	1.802 (8)	2.708 (2)	153 (1)
	O2–H2···N1GA	0.96 (1)	1.869 (8)	2.779 (2)	157 (1)
BNP4P	O1–H1···N1GA ⁱⁱ	0.97 (1)	1.783 (7)	2.748 (2)	171 (2)
	O2–H2···N1GB	0.97 (1)	1.782 (7)	2.745 (2)	169 (2)

Symmetry codes: (i) $-x + 1, -y + 1, -z$; (ii) $-x + \frac{1}{2}, y + \frac{1}{2}, z$.

guest molecules are located in channels running parallel to [010], with a cross-sectional area of $\sim 7 \times 8 \text{ \AA}^2$. The crystal packing is shown in Fig. 1(c). A typical view of the channels is shown, as an example, in Fig. 2.

The torsion angle C(2)–C(1)–C(11)–C(12), which defines the conformation of the host, varies from 83.5° in BNP3P through 95.3° in BNP2P to 103.0° in BNP4P. This is in general agreement with all the known crystal structures containing this host. A search of the Cambridge Structural Database (Cambridge Structural Database, 1999) yields 27 entries for this host molecule, with this torsion angle varying from 75 to 110° , and averaging 91° .

The results of the competition experiments are illustrated in Fig. 3. Each two-component experiment shows the mole fraction X of a given guest in the initial solution *versus* the mole fraction Z of that guest included by the host. We note

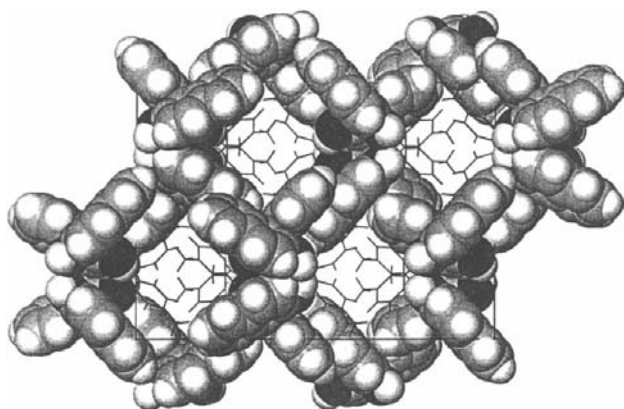


Figure 2
Space-filling projection of BNP4P along [010] with guest molecules represented as sticks, and host molecules as balls with van der Waals radii, showing the open channels.

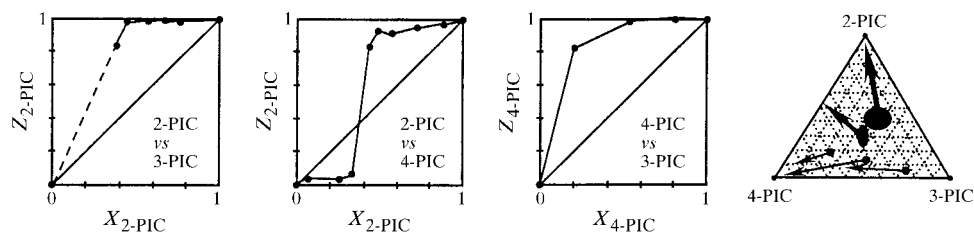


Figure 3
Results of the competition experiments. X is the mole fraction of one guest in the mother liquid, Z is the mole fraction of the same guest included in the crystal (for full details see text).

that 2-picoline and 4-picoline are both preferentially enclathrated over 3-picoline. However, the results of 2-picoline *versus* 4-picoline are concentration-dependent and the former is selected when the mole fraction of 2-picoline $X_{2\text{-pic}} > 0.4$. The three-component experiment is shown in the equilateral triangle, in which the blackened areas represent the field of the starting mixtures, while the resultant mixtures are shown by the arrows. We note that for starting mixtures with $X_{2\text{-pic}} > 0.2$, there is a migration towards 2-picoline, with the remaining mixtures moving towards 4-picoline. Under all cases 3-picoline is disfavoured.

Lattice energy calculations were performed using the program *MPA* (Williams, 1999), using a force field of the type

$$V = a \cdot \exp(-br) - c/r^6,$$

where r is the interatomic distance and the coefficients a , b and c are those given by Gavezzotti (1998). We incorporated a hydrogen-bonding potential which is a simplified form of that given by Vedani & Dunitz (1985), and is expressed as

$$V_{\text{Hbond}} = (A/R^{12} - C/R^{10}) \cos^2 \theta,$$

where R is the distance between the hydroxyl hydrogen and the N acceptor, θ is the O–H···N angle and the $\cos^2 \theta$ term is the energy penalty paid by the bond for non-linearity. This methodology was employed to calculate the lattice energies of the inclusion compounds formed between the host 1,2-bis(4-hydroxyphenyl)cyclohexane and the guests 3-picoline and 4-picoline (Caira *et al.*, 1997). We carried out summations of host···host, host···guest and guest···guest interactions, and obtained the following values for the lattice energies: BNP2P, $-222.4 \text{ kJ mol}^{-1}$; BNP3P, $-216.7 \text{ kJ mol}^{-1}$; BNP4P, $-225.6 \text{ kJ mol}^{-1}$. This result shows that the stabilities of the three inclusion compounds are in the order BNP4P > BNP2P > BNP3P. These data explain the least preferred selectivity of 3-picoline by the host. However, the competition experiment results between 2-picoline and 3-picoline are concentration dependent and we note that the lattice energies of BNP2P and BNP4P are very close, differing only by 3.2 kJ mol^{-1} . We therefore attribute this concentration-dependent selectivity to kinetic effects. This phenomenon has been noted in the separation of lutidines by a diol host compound (Caira *et al.*, 1999).

The results of the thermal analyses are shown in Fig. 4. In all of the three inclusion compounds the TG shows a one-step desolvation and exhibits the first single endothermic peak in the DSC. The last endothermic peak in the DSC corresponds to the melting of the apohost. The observed mass losses from TG for each compound are in good agreement with the calculated value and thus justify our acceptance of the host:guest ratio of 1:2 for each compound. We note that the guest release endothermic peak for BNP3P occurs at $T_{\text{on}} = 332 \text{ K}$, lower than that of the other two

compounds. The guest release endotherm for BNP2P and BNP4P occurs at about 368 and 383 K, respectively. We attribute the above to the fact that BNP3P has a less stable structure, with the least negative lattice energy of $-216.7 \text{ kJ mol}^{-1}$.

We have analysed the kinetics of desolvation of the three inclusion compounds by carrying out a series of isothermal TG runs. In all cases the resultant curves of the extent of reaction α versus time t are deceleratory and are best fitted to the kinetic model R2 (Brown, 1988). The contracting area geometrical model R2 describes a phase-boundary-controlled reaction that reacts from the edge inward on a cylindrical particle. The rate equation of R2 is stated as below

$$1 - (1 - \alpha)^{1/2} = kt.$$

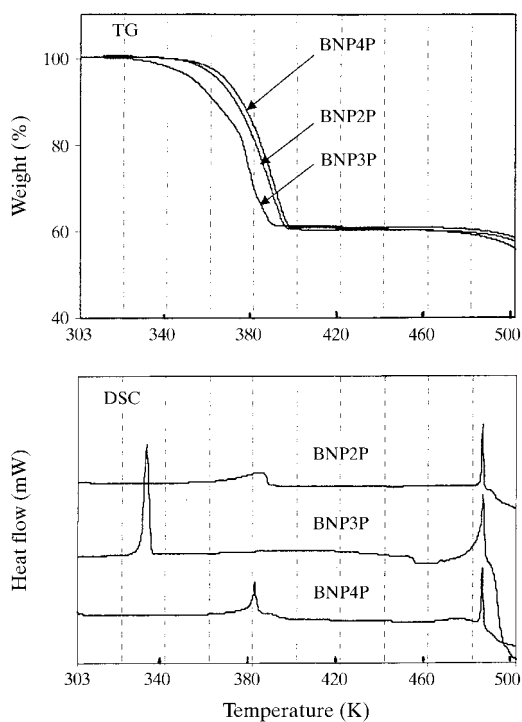


Figure 4
TG and DSC curves.

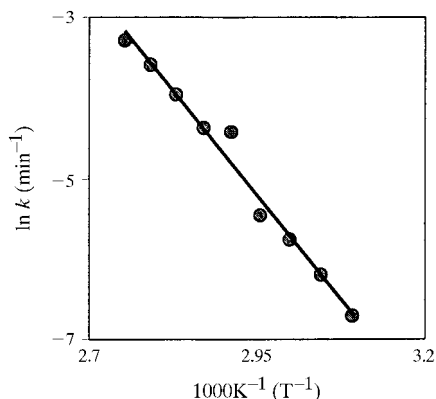


Figure 5
Arrhenius plot of $\ln k$ versus $1/T$ for the desolvation reactions of BNP2P.

According to the Arrhenius equation, $\ln k$ was plotted against $1/T$. This yielded an activation energy E_a and a pre-exponential factor $\ln A$ for each of the three compounds as follows: BNP2P: $E_a = 86 \pm 4 \text{ kJ mol}^{-1}$, $\ln A = 25 \pm 2$; BNP3P: $E_a = 82 \pm 6 \text{ kJ mol}^{-1}$, $\ln A = 26 \pm 2$; BNP4P: $E_a = 84 \pm 7 \text{ kJ mol}^{-1}$, $\ln A = 25 \pm 2$. A typical Arrhenius plot of $\ln k$ versus $1/T$, that for BNP2P, is shown in Fig. 5.

The activation energies of desolvation obtained here fall in the range $60\text{--}150 \text{ kJ mol}^{-1}$ observed for channel-type inclusion compounds (Gifford Nash, 1997), in which the guest molecules are located in channels having small physical barriers allowing facile diffusion of the guest molecules out of the host lattice.

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