9,9’-Bifluorenyl-9,9’-diol as an effective purification tool for *N*-methyl- and *N*,*N*-dimethylaniline mixtures through supramolecular chemistry strategies

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PROBLEM STATEMENT

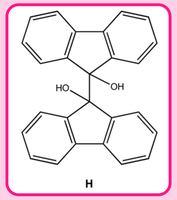
The separation of isomeric and closely related compounds remains a longstanding challenge in the chemical industry, primarily due to their similar physicochemical properties. Conventional separation techniques often prove inefficient, which prompts the need for more selective and sustainable separation strategies.[1]

ALTERNATIVE SEPARATION STRATEGY

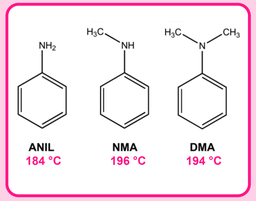
Host–guest chemistry, a branch of supramolecular chemistry,[2,3] offers an attractive, sustainable, energy-efficient and recyclable approach. These strategies utilise a host molecule, designed to selectively bind to a particular isomer through reversible noncovalent interactions (such as hydrogen bonding, π···π stacking, C–H···π close contacts and van der Waals forces), resulting in the formation of stable inclusion complexes.

AIM OF PRESENT INVESTIGATION

This investigation employed 9,9’-bifluorenyl-9,9’-diol (**H**) as a host compound for the separation of aniline (ANIL), *N*-methylaniline (NMA) and *N*,*N*-dimethylaniline (DMA) guest mixtures through host–guest chemistry strategies. All inclusion complexes were analysed by means of single crystal X-ray diffraction (SCXRD), Hirshfeld surface analysis and thermal experiments.



H



ANIL 184 °C **NMA** 196 °C **DMA** 194 °C

METHODOLOGY

H was synthesised through pinacol coupling of fluorenone with magnesium and iodine under reflux, affording a satisfactory yield of 93%.[4]

Single-solvent experiments:

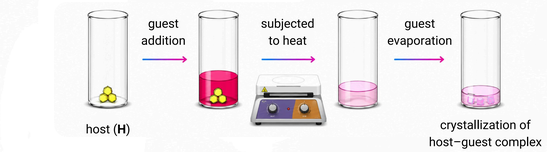


Figure 1: Preparation for single-solvent host–guest complex formation.

- Crystals collected via vacuum filtration, washed with petroleum ether, and dissolved in $CDCl_3$ for ^{1}H-NMR spectroscopic analysis.
- Host-to-guest (H:G) ratios of successfully formed complexes were determined.

Equimolar and non-equimolar guest competition experiments:

Figure 2: Preparation of equimolar (a) binary, (b) ternary, and (c) non-equimolar binary mixtures.

- Sealed vials were stored at 4 °C for crystallization. Overall H:G and guest-to-guest (G:G) ratios were determined using ^{1}H-NMR spectroscopy and gas chromatography (GC), respectively.
- Binary mixtures of Guest A and Guest B (20:80, 40:60, 60:40 and 80:20) were analysed by GC and used to construct selectivity profiles according to the model of Pivovar *et al.*[5]

RESULTS AND DISCUSSION

- **H** successfully enclathrated ANIL, NMA and DMA with 1:1, 1:1 and 3:2 H:G ratios, respectively, when it was crystallized from each of these guest solvents.
- In the equimolar guest competition experiments (Table 1), **H** preferentially included NMA, followed by ANIL, while DMA was consistently disfavoured.
- Binary guest competition experiments showed that **H** possesses the ability to separate all NMA/DMA solutions (favouring NMA), since significant host selectivities of 59.0, 73.7, 44.5, 39.3 and 48.2 were observed (Table 2). **K ≥ 10** signifies high selectivity, according to Nassimbeni and coworkers, thus **H** is an ideal candidate for effective separations in a practical setting.[6]

Table 1: Results from **H** crystallization experiments in equimolar mixed anilines.

ANIL	NMA	DMA	Guest ratios (% e.s.d.s)	Overall H:G ratio
X	X		34.5:**65.5** (1.6)	1:1
X		X	**81.0**:19.0 (0.2)	1:1
	X	X	**97.8**:2.2 (0.3)	1:1
X	X	X	32.0:**58.5**:9.5 (0.1)(0.2)(0.3)	1:1

Table 2: Calculated K values for **H** in the binary aniline mixtures.[a]

Guest (the first listed in each pair) percentage in the original solution	K values (in favour of)		
	NMA/ANIL	ANIL/DMA	NMA/DMA
20	2.0 (ANIL)	2.2 (DMA)	**59.0** (NMA)
40	1.5 (NMA)	5.2 (ANIL)	**73.7** (NMA)
50	1.9 (NMA)	4.3 (ANIL)	**44.5** (NMA)
60	1.9 (NMA)	3.7 (ANIL)	**39.3** (NMA)
80	2.8 (NMA)	1.2 (ANIL)	**48.2** (NMA)

[a]The selectivity coefficient (K) for the data points from selectivity profiles provides a quantitative measure of the host preference and was calculated using Pivovar’s equation.[5]

- SCXRD analysis of the inclusion complexes revealed that in each case, the guest molecules occupied infinite and unidirectional channels within the complex (Figure 3).

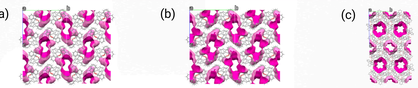


Figure 3: Void diagrams for complexes (a) **H**·ANIL, (b) **H**·NMA and (c) 3(**H**)·2(DMA).

- The isostructural nature of the host packing in the ANIL and NMA complexes is readily apparent upon comparison of Figures 3a and b.

- The preferred guest, NMA, in its complex with **H**, experienced both classical and non-classical hydrogen bonding with the host molecule, while ANIL (second preferred), in the **H**·ANIL complex, engaged only in classical hydrogen bonds; DMA (least favoured) in 3(**H**)·2(DMA), did not experience significant hydrogen bonding with the host molecule.

Table 3: Intermolecular hydrogen bonding parameters in the two complexes with **H**.

	H·ANIL (H···A, D···A, D–H···A)	**H**·NMA (H···A, D···A, D–H···A)
(host1)O–H···N(guest2)[a]	2.08 Å, 2.858(3) Å, 155°	2.15 Å, 2.912(4) Å, 151°
(host2)O–H···N(guest1)[a]	2.12 Å, 2.904(4) Å, 156°	2.13 Å, 2.905(3) Å, 153°
(guest2)C–H···O(host1)[b]	None	2.54 Å, 3.275(5) Å, 131°

[a]Classical hydrogen bonding; [b]non-classical hydrogen bonding.

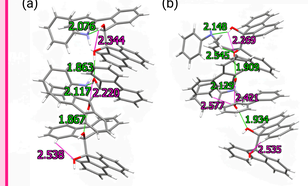


Figure 4: Hydrogen bonds (classical and non-classical) in the two complexes (a) **H**·ANIL and (b) **H**·NMA; intermolecular bonds are presented in green and intramolecular bonds in magenta.

- Also, the complex with the favoured guest, NMA, afforded a crystal with the **highest crystal density** (1.276 g·cm^{-3}) followed by ANIL (1.258 g·cm^{-3}) and the least preferred guest, DMA (1.244 g·cm^{-3}).
- Hirshfeld surface analyses revealed that the three-dimensional surfaces surrounding the ANIL and NMA guest molecules had pronounced red regions, reflecting hydrogen bonding, while the surface around DMA showed only a small red area, due to the absence of any significant hydrogen bonding.[7]

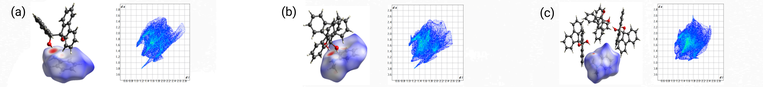


Figure 5: Hirshfeld surfaces (left) and their corresponding fingerprint plots (right) for (a) **H**·ANIL, (b) **H**·NMA and (c) 3(**H**)·2(DMA).

- Thermal analysis was performed on each complex and the onset temperatures revealed that the **H**·NMA complex (T_{on} 85.1 °C) was more thermally stable than **H**·ANIL (T_{on} 61.0 °C), while 3(**H**)·2(DMA) was unstable at ambient conditions.

Table 4: Thermal data for complexes of **H** formed with anilines.[a]

Complex	T_{on}/°C	T_p/°C	Measured mass loss/%	Expected mass loss/%
H·ANIL	61.0	185.5	23.2	20.4
H·NMA	85.1	191.5	23.3	22.8
3(**H**)·2(DMA)	[b]	185.9	[b]	18.2

[a]T_{on} is the onset temperature for the guest release event and T_p the host melt endotherm peak temperature. [b]The complex was unstable at ambient conditions.

CONCLUSION

SCXRD and Hirshfeld findings are in full agreement with the host selectivity order established in the guest competition experiments (**NMA > ANIL > DMA**). The thermal stability trend also correlates with the selectivity order. Overall, **H** proved to be an extremely capable host candidate for the effective separation of all NMA/DMA mixtures using host–guest chemistry protocols.

REFERENCES