# Evidence for the characterisation of the C–H··π interaction as a weak hydrogen bond: toluene and chlorobenzene solvates of 2,3,7,8-tetraphenyl-1,9,10-anthyridine

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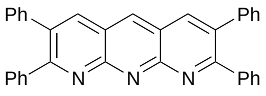
**The crystal structures of the toluene and chlorobenzene solvates of 2,3,7,8-tetraphenyl-1,9,10-anthyridine are nearly identical save for differences in the mode of solvent inclusion; these differences have an important bearing on the nature of the C–H··π interactions in these structures.**

During the synthesis[1] and purification of 2,3,7,8-tetraphenyl-1,9,10-anthyridine **1**‡ it was noticed that the compound failed to yield crystals for X-ray analysis from several solvents such as anisole, benzene, chloroform, ethyl acetate, mesitylene, nitrobenzene, pyridine and xylene, ill-defined powders being obtained in every case. Curiously, well-formed bright yellow crystals were obtained easily from toluene and analysis showed that they correspond to the 1 : 1 solvate **2**. Noting that the methyl group is replaceable by the chloro group without a change in crystal structure (the so-called 'chloro–methyl exchange rule')[2] recrystallisation was attempted from chlorobenzene and we were not surprised to find that in this case too diffraction-quality crystals, now of the corresponding 1 : 1 solvate **3**, were obtained. The crystal structures of the toluene and chlorobenzene sovlates, **2** and **3**, were then determined at low temperature and to good precision.§ While the structures are very similar, with nearly the same unit cell dimensions and space group symmetry, there are small differences with respect to the positioning of the solvent molecules. Although small, these differences are significant and show that the C–H··π interactions found in these structures have the characteristics of weak hydrogen bonds.



**1**

**2** = **1**•toluene
**3** = **1**•chlorobenzene

Figs. 1 and 2 show the crystal structures of solvates **2** and **3**. The positioning of the heterocyclic molecule in the two unit cells is identical and so are the gross packing features.¶ Fig. 1 shows that the ordered toluene molecule in **2** is situated in a pocket formed by three molecules of **1**. Inspection of Fig. 2 shows that the ordered chlorobenzene molecule in **3** is situated in a nearly identical pocket. However, the Me and Cl substituents point in almost opposite directions in the two cases. This is unusual. When chloro–methyl exchange is obtained, the two substituents behave in an isosteric fashion with only shape and size factors controlling the packing.[2] The switching around of the substituent Me and Cl groups in **2** and **3** is indicative of the fact that electronic factors are involved in stabilisation of the solvent molecule in one or both cases.

A very short C–H··π interaction of 2.54(2) Å (all H-atom positions normalised in this and subsequently discussed contacts) in **2** (**a** in Fig. 1) is noteworthy. This interaction is clearly of the H··ring centroid type ($\theta$ = 151°),[3] the distances from the H-atom to the six ring atoms of the toluene molecule lying in the range 2.73–3.05 Å. Such H··centroid distances have been reported previously[3,4] but are definitely at the short end of the accepted distance range for this contact.[5] Accompanying contact **a** is a much longer contact of 3.01 Å ($\theta$ = 126°, **b** in Fig. 1) so that the toluene molecule may be said to be positioned at unequal distances from adjacent glide-related molecules of anthyridine **1**. In contrast, let us consider the two corresponding contacts, **g** [2.61(2) Å, $\theta$ = 143°] and **h** [2.62(2) Å, $\theta$ = 147°] in **3** (Fig. 2). These are formed by C–H groups that are chemically equivalent and therefore of the same acidity as the C–H group that forms contact **a** in **2**. However, contacts **g** and

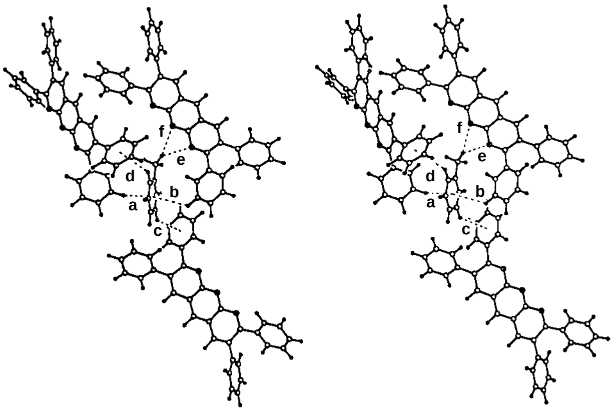


**Fig. 1** Stereoview of the crystal structure of solvate **2** approximately down [010], showing the binding of the toluene molecule. The anthyridine molecules are inversion- and glide-related. Interactions **a**–**f** are indicated. Notice the cooperative scheme of C–H··π hydrogen bonds and the positioning of the methyl H-atom between the two heterocyclic N-atoms. Interaction **a** is unusually short.

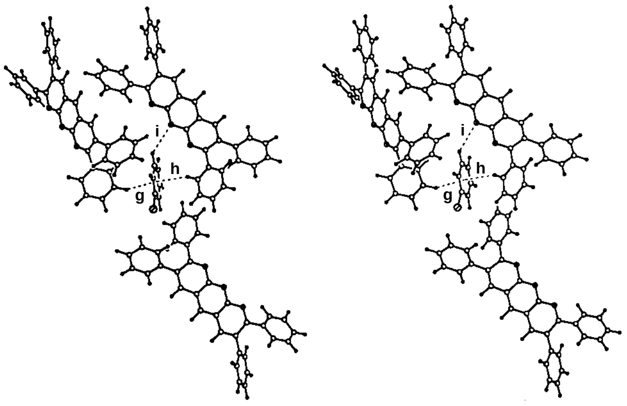


**Fig. 2** Stereoview of the crystal structure of solvate **3** showing the binding of the chlorobenzene molecule. Interactions **g**–**i** are indicated. Contrast this with Fig. 1. Notice that the Cl-atom is not involved in any specific intermolecular contact.

**h** are significantly longer than contact **a**. Unlike the toluene molecule in **2**, the chlorobenzene molecule in **3** may therefore be considered as being disposed at nearly equal distances to the adjacent molecules of **1**.

In general, short intermolecular distances such as **a** in **2** are taken as evidence of crystal stabilisation but it should be noted that shortness alone does not constitute proof of an attractive interaction. It is always possible that a short contact is repulsive and that it arises from the overall balance of interactions in a crystal structure.[6] However, when as in this case, the shortness of **a** with respect to **g** and **h** also correlates with the electron-rich character of the aromatic ring in toluene *vis-a-vis* chlorobenzene, and also given that there would be little steric problem were the toluene molecule to be placed symmetrically between the two approaching C–H groups, one may state with confidence that the C–H··π interaction **a** is stabilised by the electron rich aromatic ring in toluene. Hydrogen bonds of all types are fortified by increasing acidities and basicities of donor and acceptor groups, respectively,[7,8] and our observations here adduce evidence that the C–H··π interaction has structural properties of weak hydrogen bonds, similar to O–H··π and N–H··π interactions.[9] Because of its weakness, however, it is difficult in general to obtain clear evidence for the existence of this type of hydrogen bond. It is possible to do so in this case because structures **2** and **3** are similar in just about every respect except the interaction of interest.

Hydrogen bonds formed by carbon acids and π-bases are soft and this in turn can lead to the cooperative patterns of interactions.[10–13] Again, the structure of **2** is revealing. It would seem that the weak hydrogen bond **a** is able to activate the C–H groups in the toluene molecule at least to the extent that the long contacts **c**–**f** are possible. Interactions **c** (2.90 Å, $\theta = 140°$) and **d** (3.01 Å, $\theta = 140°$) formed by the aromatic C–H groups are the C–H··π type while interactions **e** (2.76 Å, $\theta = 146°$) and **f** (2.83 Å, $\theta = 161°$) formed by the methyl C–H groups are of the C–H··N type. Although long, these contacts are within the accepted distance ranges.[5,11] In contrast, there is just one extra interaction of the C–H··N type in the unactivated structure **3** (**i**; 2.87 Å, $\theta = 139°$). All these interactions may make only small contributions to the crystal binding energy but they help in defining the structures of the solvates. For example, it is possible that these secondary interactions are the causes for the opposite orientations of the toluene and chlorobenzene molecules referred to above and also to the fact that the solvent molecules are ordered in **2** and **3**. It is pertinent to state here that of the 1171 toluene and 75 chlorobenzene solvates in the Cambridge Structural Database (CSD, April 1997, version 6.2, 167 797 entries) for which coordinates are available, the solvent is ordered in only 413 and 35 structures, respectively.‖ Although the binding of chlorobenzene in the anthyridine pocket is poorer than that of toluene, it is still not just shape-controlled; compound **1** failed to form diffraction-quality crystals with either fluorobenzene or bromobenzene. In this regard, the formation of solvates **2** and **3** is reminiscent of guest-induced host crystallisation of the type encountered in the benzene solvate of the mono-enol form of cyclohexane-1,3-dione.[14]

Since the pioneering work of Nishio, who first postulated the existence of the C–H··π interaction,[15] much work has been done in this area. With the current interest in crystal engineering and supramolecular chemistry, there is now a new appreciation for this form of intermolecular association. The hydrogen bond is an attractive, directional interaction which, though predominantly electrostatic, also has polarisation and charge transfer characteristics. While it has always been recognised that C–H··π interactions in highly activated systems such as terminal acetylenes are of the hydrogen bond type, the present work shows that even moderately activated systems such as tolyl rings participate in interactions that may be considered to be weak hydrogen bonds formed by soft acids and soft bases. In this regard, it could be stated that the grey area between the weak hydrogen bond and the herringbone interaction is gradually diminishing.

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## Footnotes and References

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‡ *Synthesis* of **1**: as described in ref. 1 *via* the Friedländer condensation of 2,6-diaminopyridine-3,5-dicarbaldehyde with deoxybenzoin.

§ *Crystal data* for **2**: 2,3,7,8-tetraphenyl-1,9,10-anthyridine–toluene 1 : 1 solvate ($C_{35}H_{23}N_3{\cdot}C_7H_8$, $M = 577.70$). Monoclinic, space group $P2_1/c$; $a = 17.543(5)$, $b = 9.308(4)$, $c = 18.972(4)$ Å, $\beta = 98.58(1)°$, $V = 3063(2)$ Å$^3$, $Z = 4$, $D_c = 1.25$ g cm$^{-3}$, Enraf Nonius FAST area detector, $T = 120$ K, Mo-K$\alpha$, $\omega$–$\theta$ scan mode, 6891 unique reflections, 5155 with $F^2 > 2\theta(F^2)$, no absorption corrections. Structure solution and refinement with standard methods (SHELXS86 and SHELXL93); H-atoms refined isotropically. Final $R = 0.050$ (observed), 0.066 (all), $wR(F^2) = 0.130$ (observed), 0.152 (all).

For **3**: 2,3,7,8-tetraphenyl-1,9,10-anthyridine–chlorobenzene 1 : 1 solvate ($C_{35}H_{23}N_3{\cdot}C_6H_5Cl$, $M = 598.11$). Monoclinic, space group $P2_1/c$; $a = 17.646(4)$, $b = 9.319(3)$, $c = 18.807(2)$ Å, $\beta = 100.48(1)°$, $V = 3041.1(12)$ Å$^3$, $Z = 4$, $D_c = 1.31$ g cm$^{-3}$, Enraf Nonius FAST area detector, $T = 120$ K, Mo-K$\alpha$, $\omega$–$2\theta$ scan mode, 6802 unique reflections, 4121 with $F^2 > 2\sigma(F^2)$, no absorption corrections. Structure solution and refinement with SHELXS86 and SHELXL93; H-atoms refined isotropically. Final $R = 0.046$ (observed), 0.082 (all); $wR(F^2) = 0.113$ (observed), 0.214 (all). CCDC 182/598.

¶ The near identity of the packing of the anthyridine molecules in the two structures was also quantified with an inspection of the NIPMAT plots for the two structures. For a description of the NIPMAT procedure, see ref. 11. We thank Dr S. R. Rowland for making available a copy of this program.

‖ However, we found only two pairs of isostructural toluene and chlorobenzene solvates (KERREE, KERROO; KERRII, KERRUU) in these CSD searches.

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