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The utility of 4-aminobenzoic acid in promotion of hydrogen bonding in crystallization processes: the structures of the cocrystals with halo and nitro substituted aromatic compounds, and the crystal structures of the adducts with 4-nitroaniline (1:1), 4-(4-nitrobenzyl)pyridine (1:2), and (4-nitrophenyl)acetic acid (1:1)

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A number of molecular adducts of 4-aminobenzoic acid (4-ABA) have been prepared and characterized using infrared spectroscopy and in three cases by X-ray diffraction methods. These three compounds are with 4-nitroaniline [(4-ABA) ($C_6H_6N_2O_2$)], 4-(4-nitrobenzyl) pyridine, [(4-ABA)$_2$ ($C_{12}H_{10}N_2O_2$)$_4$], and (4-nitrophenyl)acetic acid, [(4-ABA) ($C_8H_7NO_4$)]. Other compounds described are with 4-chlorobenzoic acid, [(4-ABA) ($C_7H_5ClO_2$)], 4-bromobenzoic acid, [(4-ABA) ($C_7H_5BrO_2$)], 4-cyanobenzoic acid, [(4-ABA) ($C_7H_6N_2$)], 2-nitrobenzoic acid, [(4-ABA) ($C_7H_5NO_4$)], and 3-nitrobenzoic acid, [(4-ABA) ($C_7H_5NO_4$)]. All compounds have 1:1 stoichiometry except that with 4-(4-nitrobenzyl)pyridine (1:2) which is unique in being retro-stoichiometric. A review of the systematics of the 4-aminobenzoic acid adducts is also made, particularly with respect to the infrared characterization of the cocrystalline materials and prediction of their NLO potential.

KEY WORDS: Cocrystals; molecular adducts; carboxylic acids; 4-aminobenzoic acid.

Introduction

4-Aminobenzoic acid (4-ABA) is one of the most versatile of the carboxylic acids for cocrystal formation, promoting molecular self-assembly via hydrogen bonding through both the carboxylic acid group and the ring-substituted amino group. Since the first crystallographic characterization in 1984 of a 1:1 adduct with 4-nitropyridine-N-oxide,[1] only three other complexes had been described until the work completed by our group. These were with 1,3-dimethyl-1-imidazolidinone [(4-ABA) (DMI)][2] and 3,5-dinitrobenzoic acid [(4-ABA) (DNBA)][3] (both 1:1), while the third, a 2:1 inclusion adduct with 18-crown-6 had been partially characterized.[4] The current list includes eight additional adducts, four with carboxylic acids, two with Lewis bases, one with a neutral organic species and one with both an acid and a neutral species. The organic acids involved are (2,4-dichlorophenoxy)acetic acid, [(4-ABA) (2,4-D)],[5] (2-carboxyphenoxy) acetic acid, [(4-ABA) (CPAA)][6] pyrazine-2,3-dicarboxylic acid, [(4-ABA)$^+$ (PDCA)$^-$],[7] 2,4,6-trinitrobenzoic acid, [(4-ABA)$^+$ (TNBA)$^-$ (H_2O)],[8] and the only reported 2:1 adduct with 3,5-dinitrosalicylic acid, [(4-ABA) (4-ABA)$^+$ (DNSA)$^-$],[9] the third example in which proton transfer occurs. In all of these, the acid is sufficiently strong to protonate the amino group of

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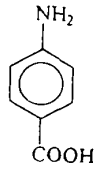
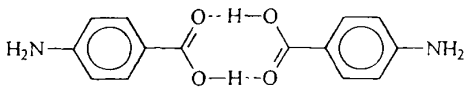
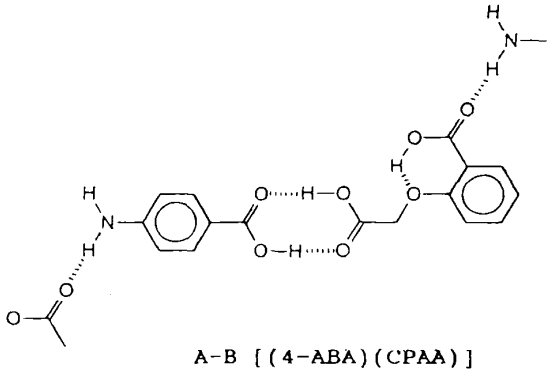
4-ABA, this group subsequently being involved in hydrogen bonding interactions with up to five acceptor centers, promoting stability in the resulting cocrystal system. With the 2:1 adduct, the primary association is between two 4-ABA molecules giving a cyclic hydrogen bonded **A−A** homodimer [graph set $R_2^2(8)$[10]], similar to that found not only in the solid-state structure of the parent acid (4-ABA)[11] but in the majority of the carboxylic acids. In contrast, the complex [(4-ABA) (CPAA)] has a primary **A−B** R_2^2 (8) interaction between the heteromolecular pair (4-ABA and the phenoxyacetic acid group of CPAA), with secondary carboxylic acid (the benzoic acid) to amine group hydrogen bonding giving a chain structure.



4-ABA



A-A [(4-ABA)2]

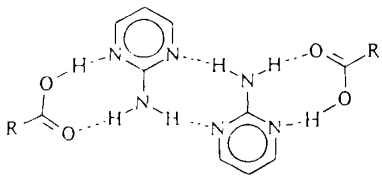


A-B [(4-ABA)(CPAA)]

The adduct with the heterocyclic base 2-aminopyrimidine, [(4-ABA) (2-AP)], has the primary **A−P−P−A** hydrogen bonding association, characteristic of this molecule with carboxylic acids.[12] Each **A−P−P−A** unit is also linked laterally to the amino group of a symmetry-related 4-ABA molecule by hydrogen bonding associations through both amine protons, giving a 2-dimensional layer structure.[13]

Another analogous but simpler **A−P** system involving 4-ABA and the substituted pyrimidine, 4-amino-*N*-(4,6-dimethyl-2-pyrimidinyl)benzenesulfonamide, [(4-ABA) (4-APBS)] has also been characterized.[14] The historically significant red complex formed between 4-ABA and 1,3,5-trinitrobenzene (TNB).[15] has also been determined as a 1:1 adduct [(4-ABA) (TNB)] with a primary **A−A** association between two 4-ABA molecules while the TNB molecules are held in essentially π bonding interactions.[16] The 4-ABA-2,4,6-trintitrobenzoic acid system (obtained from the solid-state interaction of the two components), when recrystallized from water, yielded not only this same compound [(4-ABA) (TNB)] as a minor product but also yellow [(4-ABA)$^+$(TNBA)$^-$(H_2O)][8] as a major product and the unusual (3:1:1) triheteromolecular cocrystal, [(4-ABA)$_2$(4-ABA)$^+$ (TNBA)$^-$(TNB)],[17] the TNB being derived from the partial decarboxylation of the TNBA.[18] Other chemically characterized cocrystals of 4-ABA for which X-ray data are not available are the adducts with 4-methyl-3,5-dinitrobenzoic acid,[19] 4-nitrobenzoic acid,[20] and 3,5-dinitrobenzamide.[19] Two (1:1) adducts of the substituted 4-ABA compound 4-(*N,N'*-dimethylamino) benzoic acid, the first with 3,5-dinitrocinnamic acid, [(DMABA) (DNCA)], the second with 3,5-dinitrobenzoic acid, [(DMABA)$_2$(DNBA)$_2$],[21] are worthy of note. Although the first involves conventional A−B heterodimers, the second has two unique A−A homodimers.

The structures reported here, the cocrystalline products from the interaction of a series of halo and nitro substituted aromatic compounds with 4-aminobenzoic acid represent a series with the properties necessary for extended hydrogen bonding structure formation via secondary group interactions, hence possessing asymmetry potential, an important criterion for



A-P-P-A [(4-ABA)$_2$(2-AP)$_2$]

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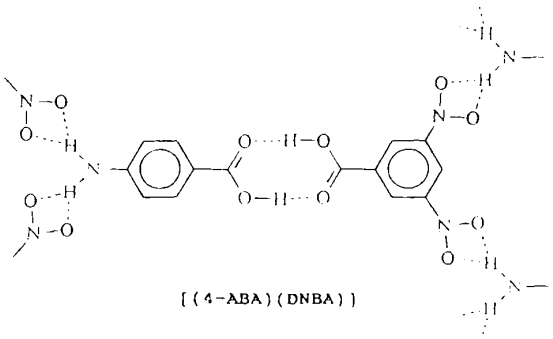
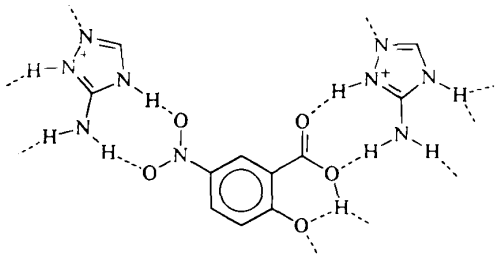
nonlinear optical applications.[22,23] With nitro substituted compounds, participation of this group in hydrogen bonding associations with cocrystal formation has been found in a number of structures, including [(4-ABA) (DNBA)][3] and [(4-ABA)(4-ABA)$^+$(DNSA)$^-$].[9] In the DNBA structure, in which no proton transfer occurs, both nitro oxygens in the first order network **A–B** structural unit form three-center associations with two amine protons of adjacent units in the layer structure.

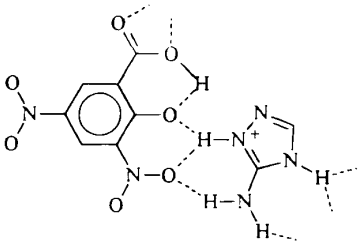


[(4-ABA)(DNBA)]

Although this behavior would suggest (at least in this cocrystal) that nitro group participation is part of the secondary structure, examples are known, particularly with those involving proton transfer, in which nitro groups appear to be involved in the primary interaction.[24] However, such interactions may be aided by proximal group participation, as is found in the 1:1 complexes of 3-amino-1,2,4-triazole with 5-nitrosalicylic acid [(3-AT)$^+$(5-NSA)$^-$] and 3,5-dinitrosalicylic acid [(3-AT)$^+$ (DNSA)$^-$].[24]

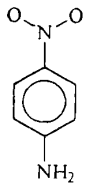


[(5-NSA)(3-AT)]

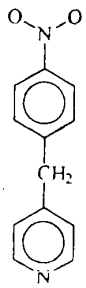


[(DNSA)(3-AT)]

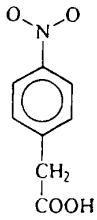
The adducts of 4-ABA are with 4-nitroaniline (4-NA), [(4-ABA) (4-NA)], **1**; 4-(4-nitrobenzyl)pyridine (4-NBP) [(4-ABA)$_2$(4-NBP)$_4$], **2**; 4-nitrophenylacetic acid (4-NPA), [(4-ABA) (4-NPA)], **3**; 4-chlorobenzoic acid (4-CBA), [(4-ABA) (4-CBA)], **4**; 4-bromobenzoic acid (4-BBA), [(4-ABA) (4-BBA)], **5**; 4-cyanobenzoic acid (4-CNBA), [(4-ABA) (4-CNBA)], **6**; 2-nitrobenzoic acid (2-NBA), [(4-ABA) (2-NBA)], **7** and 3-nitrobenzoic acid (3-NBA), [(4-ABA) (3-NBA)], **8**. The crystal structures of compounds **1–3** have been determined by single crystal X-ray diffraction. Compound **2** is unusual in that it represents not only a rare example of a combination giving other than a 1:1 cocrystal but is also the first example in which 4-ABA forms a retro-stoichiometric complex, with a 1:2 rather than a 2:1 stoichiometry.



(4-NA)



(4-NBP)



(4-NPA)

Experimental

Preparations

Complexes **1–8** were prepared using equimolar amounts (2.2mmol) of 4-aminobenzoic acid (4-ABA) and respectively 4-nitroaniline (4-NA), (**1**); 4-(4-nitrobenzyl)pyridine (4-NBP), (**2**); 4-nitrophenylacetic acid (4-NPA), (**3**); 4-chlorobenzoic acid (4-CBA), (**4**), 4-bromobenzoic acid (4-BBA), (**5**); 4-cyanobenzoic acid (4-CNBA), (**6**); 2-nitrobenzoic acid (2-NBA), (**7**) and 3-nitrobenzoic acid (3-NBA), (**8**). All preparations involved refluxing for 20 mins. at *ca.* 110°C in 40cm^3 of 95% ethanol, the product being subsequently

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obtained by the total evaporation of the solvent at room temperature: for **1**, yellow plates (mp 151–153°C); for **2**, pale brown needles (mp 139–141°C); for **3**, yellow prisms (mp 136–138°C); for **4**, **5**, and **6**, pale brown powders (mp 188–190, 204–205.5 and 204–206°C respectively); for **7** and **8**, yellow powders (mp 131.5–133.5 and 170–173°C respectively). Analyses indicated 1:1 stoichiometries for all compounds except **2** which was 1:2. [Found for **1**: C, 56.5; H, 4.7; N, 15.6%. $C_{13}H_{13}N_3O_4$ requires C, 56.7; H, 4.8; N, 15.3%. Found for **2**: C, 65.6; H, 4.8; N, 12.3%. $C_{31}H_{27}N_5O_6$ requires C, 65.8; H, 4.8; N, 12.4%. Found for **3**: C, 57.3; H, 4.5; N, 8.7%. $C_{15}H_{14}N_2O_6$ requires C, 56.6; H, 4.4; N, 8.8%. Found for **4**: C, 60.5; H, 4.4; N, 4.9%. $C_{14}H_{12}ClNO_4$ requires C, 57.3; H, 4.1; N, 4.8%. Found for **5**: C, 52.0; H, 3.6; N, 4.3%. $C_{14}H_{12}BrNO_4$ requires C, 49.7; H, 3.6; N, 4.1%. Found for **6**: C, 62.9; H, 4.2; N, 9.6%. $C_{15}H_{12}N_2O_4$ requires C, 63.4; H, 4.3; N, 9.9%. Found for **7**: C, 55.3; H, 3.9; N, 9.4%. Found for **8**: C, 56.0; H, 3.8; N, 9.8%. $C_{14}H_{12}N_2O_6$ requires C, 55.3; H, 4.0; N, 9.2%]. Infrared spectra were recorded for all samples as pressed KBr disks on a Perkin-Elmer 1600 Fourier-transform infrared spectrometer. The use of other than 1:1 stoichiometric ratios of reactants in the preparations invariably resulted in the formation of the same products **1–8**. In those examples where suitable crystals for single crystal X-ray analysis could not be obtained, cocrystal formation was also identified by powder diffraction, the *d*-spacings (Å) and the normalized intensities (*I/Io*) for the three strongest lines for **4–8** being as follows: for **4**, 3.22(100), 4.82(90), 3.63(70); for **5**, 3.27(100), 3.70(90), 4.69(70); for **6**, 4.70(100), 3.60(70), 3.90(70); for **7**, 5.71(100), 7.14 (80), 3.74 (70); for **8**, 5.64 (100), 3.22 (100), 3.41 (60). For 4-aminobenzoic acid, comparative *d*(*I/Io*) values are 5.76(100), 3.62(93), 6.39(73). Qualitative second harmonic generation (SHG) measurements on powdered samples were carried out by using a Quantel 470 Q-switched Nd:YAG laser with 20mJ pulses at 1Hz.

Crystal data, data collection, structure solution and refinement

Details of cell data, X-ray data collection, structure solution and refinement are given in Table 1. Structures were solved by direct methods (*SHELXS*-86)[25]. Full-matrix least-squares refinement (on F^2) (*SHELXL*-93)[26] with anisotropic thermal parameters for all non-hydrogen atoms was used. Hydrogens involved in the hydrogen bonding interactions were located by difference methods and both positional and thermal parameters were refined while others were either located or included at calculated positions in the refinements as riding models. It is of note that for **2**, intensity statistics and general systematic absences indicated the centrosymmetric space group $P2_1/n$, in which a structure solution was obtained but a refinement residual of no better than 9% could be obtained. However, a close examination of the data revealed a significant number of extinction violations for $P2_1/n$ (for $h0l$, $h+l$ = odd, expected absent) so that the subsequent successful solution and refinement in the non-centrosymmetric space group $P2_1$ indicates the presence of subtle pseudo *n*-glide symmetry in the crystals.

Results and discussion

Final atomic coordinates are listed in Table 1. Bond distances and angles, anisotropic thermal parameters, hydrogen atom coordinates and observed and calculated structure factors for adducts **1–3** have been deposited and are available on request. In the structures of 1 and 3, molecule A refers to 4-aminobenzoic acid while molecule B refers to the second adduct molecule. With **2**, molecules A and B are 4-aminobenzoic acid while molecules C–F are 4-(4-nitrobenzyl)pyridine. Atom numbering schemes for the two associated molecule types and the hydrogen bonding schemes are shown in Figs. 1–3.

*The structures of complexes **1–3***

In the structure of the 1:1 complex of 4-aminobenzoic acid with 4-nitroaniline (4-NA), [(4-ABA) (4-NA)] **1**, a relatively simple association is found (Fig. 1). The primary interaction is between the carboxylic acid groups of two inversion-related 4-ABA pairs giving a cyclic hydrogen bonded **A–A** dimer [graph set R_2^2 (8)] [O(11A)-H(11A)---O(10A), 2.659(7)Å; O–H---O, 172(6)°]. This dimer is similar to that found in the parent acid[11] as well as to that in some of the adduct structures of 4-ABA, including those in which proton transfer occurs, e.g., in [(4-ABA) (4-ABA)$^+$ (DNSA)$^-$].[9] In addition to this primary association, a secondary lateral interaction occurs between one of the carboxylic acid oxygens of 4-ABA and one of the amine protons of 4-NA [O(10A)---H(11B)–N(11B),

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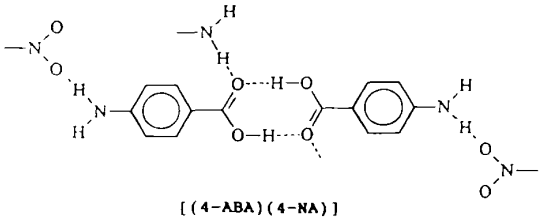
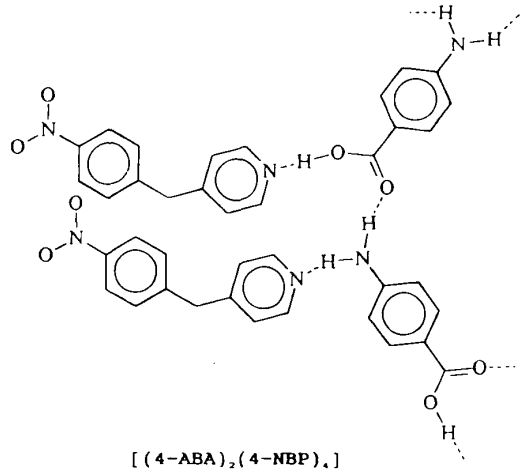
3.049(7)Å, O---H-N, 166(6)°], while this nitrogen gives a further lateral link to a symmetry related 4-ABA amine proton [N(11B)---H(42A)−N(41A), 3.245(7)Å, N---H−N, 137(6)°]. One more association between the second 4-ABA amine proton and a 4-NA nitro oxygen [N(41A)−H(41A)---O(40B), 3.250(7)Å, N-H---O, 160(6)°], completes the two-dimensional hydrogen bonding pattern, giving a layer structure which lies parallel to the *bc* plane.



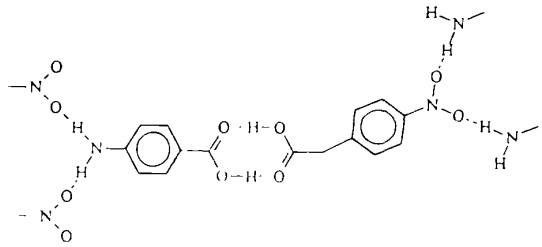
[(4-ABA)(4-NA)]

Compound **2** is an unusual pseudo-centrosymmetric 2:4 adduct of 4-ABA with 4-(4-nitrobenzyl)pyridine, $[(4\text{-ABA})_2(4\text{-NBP})_4]$, in which the primary interaction between the two independent 4-ABA molecules (A and B) is head to tail *via* single weak hydrogen bonds between the carbonyl oxygen and the amine group of the adjacent molecule [O(10A)---H(41B)−N(41B), 3.326(5)Å, O---H−N, 175(4)°: O(10B)---H(41A)−N(41A), 3.356(5)Å, O---H−N, 175(4)°]. This gives a zig-zag ribbon structure extending along the *c* direction of the cell (Fig. 2). A parallel stack of alternating 4-NBP molecules (molecules C–F) tie into this basic chain *via* single hydrogen bonds between their pyridine nitrogens and the second amine nitrogen of the 4-ABA molecules [N(41B) −H(42B)---N(1C), 3.039(5)Å, N-H---N, 157(4)°: N(41A)-H(42A)---N(1D), 2.990(5)Å, N-H---N, 160(4)°] and the second carboxylic oxygen [O(11A) −H(11A)---N(41E), 2.654(5)Å, O-H---O, 159(4)°: O(11B) −H(11B)---N(1F), 2.663(5)Å, O-H---N, 152(4)°]. All carboxyl protons were located and satisfactorily refined, and support the spectroscopic evidence indicating no proton transfer from 4-ABA to the pyridine nitrogen. The value of ΔpK_a, the difference between the pK_a values for similar substituted pyridines and 4-ABA, is estimated to be >3.75, which is considered the minimum for proton transfer to occur at least with pyridine complexes.[27] This suggests that compound 2 could involve proton transfer, which might justify the unusual and unique occurrence of the 1:2 retro-stoichiometry, just as the 2:1, 4-ABA to strong acid ratio {such as found in the complex $[(4\text{-ABA})(4\text{-ABA})^+(\text{DNSA})^-]$[9]} only occurs after proton transfer to 4-ABA. However, this is not the case. In addition, the nitro oxygens are not involved in the stabilization of the herringbone structural motif except for possible C−H---O interactions[28] [C(6B)−H(6B)---O(40C), 3.373(5)Å, C−H---O, 147(4)°].



$[(4\text{-ABA})_2(4\text{-NBP})_4]$

Structure **3**, the 1:1 adduct of 4-ABA with (4-nitrophenyl) acetic acid, [(4-ABA) (4-NPA)], is based on a primary cyclic hydrogen bonded **A−B** heterodimer pair similar to **1** [O(11A)−H(11A)---O(20B), 2.740(9)Å; O−H---O, 161(7)°; O(12A)---H(21B)−O(21B), 2.592(9)Å; O---H−O, 161(7)°]. The two nitro oxygens are then weakly associated with the amine protons of adjacent translated 4-ABA molecules [N(41A)−H(41A)---O(41B), 3.161(9)Å; N−H---O, 158(8)°] [N(41A)−H(42A)---O(40B), 3.134(8)Å; N−H---O, 141(8)°], giving a two-dimensional sheet structure which stacks down the *a* cell direction (Fig. 3).



[(4-ABA)(4-NPA)]

Spectroscopy

As previously described,[12] heteromolecular dimer formation between carboxylic acid groups can also be

Table 1. Crystal data for [(4-ABA) (4-NA)], (**1**), [(4-ABA)$_2$(4-NBP)$_4$], (**2**), and [(4-ABA) (4-NPA)], (**3**)

Compound	(**1**)	(**2**)	(**3**)
Formula	$C_{13}H_{13}N_3O_4$	$C_{62}H_{54}N_{10}O_{12}$	$C_{15}H_{14}N_2O_6$
M_r	275.3	1131.2	318.3
Color, shape	yellow plates	brown needles	yellow prisms
Space group	$P2_1/c$	$P2_1$	$P2_1/a$
a (Å)	4.869 (3)	10.052 (2)	15.272 (2)
b (Å)	31.25 (1)	17.973 (3)	5.910 (2)
c (Å)	8.637 (6)	15.883 (3)	17.194 (2)
β(°)	93.69 (4)	103.173 (8)	108.80 (2)
V (Å^3)	1311 (1)	2794.0 (9)	1469.1 (6)
Dc (g cm^{-3})	1.394	1.345	1.439
Z	4	2	4
μ (cm^{-1})	1.06	0.95	1.13
F(000)	576	1184	664
Temperature (°C)	25 (2)	25 (2)	25 (2)
Data collection			
a. Crystal size (mm)	0.30×0.25×0.12	0.50×0.30×0.25	0.40×0.30×0.12
b. $2\theta_{max}$ (°)	50	50	50
c. Unique data	2299	10410	2570
d. Collection range (h,k,l)	5, 37, ±10	11, ±21, ±18	18, 7, −20 to 19
e. Data used	1006	5911	840
f. Discrimination	$I>2\sigma(I)$	$I>2\sigma(I)$	$I>2\sigma(I)$
g. $R1$[a]	0.051	0.042	0.058
h. $wR2$[b]	0.151	0.113	0.180
i. GOF	0.82	0.94	0.90
j. w[c] A	0.176	0.093	0.206
B	0.93	0.03	0.00
k. Max. Residual peak (e Å^{-3})	0.14	0.11	0.15

[a] $R1$ [$= \Sigma\{ \| F_o\| - \| F_c \| / \| F_o \| \}$].
[b] $wR2$ [$= \{\Sigma w(F_o^2 - F_c^2)^2/\Sigma w(F_o^2)\}^{1/2}$], with
[c] $w=[\sigma^2F_o^2 + (AP)^2 + BP]$, where P = [max ($F_o^2$, 0) + $2F_c^2$]/3.

detected using infrared spectroscopy. By comparing characteristic absorptions in the IR spectra, Etter was able to confirm that the (1:1) 4-ABA adduct with 4-chloro-3,5-dinitrobenzoic acid complex was structurally similar to the known 1:1 complex of 4-ABA with DNBA [(4-ABA) (DNBA)]. Characteristic IR absorptions for the two complexes include a N−H peak at 3488cm^{-1}, and a C=O stretch at 1687cm^{-1}. Further evidence indicating the formation of a carboxylic acid dimer, of any type, may be found in the presence of a broad asymmetric peak at *ca.* 3300–2300cm^{-1} due to O−H stretching and a broad medium-intensity band in the 960–875cm^{-1} region, characteristic of O−H---O out-of-plane hydrogen bond deformation.[29] Complex **1**, comprising two neutral molecules, displays this in the IR region. Carboxylic acid dimer formation is evident from a broad asymmetric peak at *ca.* 3300–2300cm^{-1} as well as a broad medium-intensity band at 926cm^{-1}. Interestingly, the C=O stretch is observed at a lower frequency than usually expected (1663cm^{-1}). This could be due to the additional hydrogen bonding interaction involving the amino group on 4-NA. A third, lower frequency N−H stretch is also observed at 3226cm^{-1} *cf.* the usual two stretching frequencies at 3430 and 3348cm^{-1}. Complexes **3–8** all involve hetero-dimer formation, as confirmed in the crystal structure of **3** and from the spectroscopic evidence. Characteristics N−H peaks ranging from 3498–3459 and 3396–3392cm^{-1} together with sharp carbonyl stretches ranging from 1686–1678cm^{-1} are evident in each spectrum. Furthermore, broad O−H stretching peaks (*ca.* 3000cm^{-1}) as well as O−H---O out-of-plane deformation peaks occur from 930–920cm^{-1}. In comparison, proton transfer complex formation is identified in the infrared region by the presence of N$^+$−H and CO_2^- frequencies. Protonated tertiary amines absorb in the infrared in the 2500–1800cm^{-1} region with medium to broad bands, due to

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overtones and combinations, as well as a medium to weak peak between 1670 and 1610cm^{-1}. Carboxylate ions have strong antisymmetric and symmetric stretching frequencies between 1610–1550 and 1420–1300cm^{-1} respectively. However, infrared data for 2 support the crystallographic evidence which confirms that 4-(4-nitrobenzyl)acetic acid is not sufficiently strong to protonate 4-aminobenzoic acid.

In addition, unpublished infrared spectroscopic data on 1:1 cocrystals of 2-aminobenzoic acid (2-ABA) with 2-nitrobenzoic acid (2-NBA) and 3-nitrobenzoic acid (3-NBA),[4] and 3-aminobenzoic acid (3-ABA) with 2-NBA, and 3-NBA[5] confirm that the two 2-ABA compounds are hetero-dimers while the two 3-ABA compounds exhibit proton transfer complex characteristics.

Effect of pKa

It has been shown from both the X-ray structures and IR spectroscopy, that 4-aminobenzoic acid

[4] For 2-aminobenzoic acid with 2-nitrobenzoic acid [(2-ABA) (2-NBA)], and 3-nitrobenzoic acid [(2-ABA) (3-NBA)], the total evaporation of ethanol at room temperature yeilded: light brown needle crystals (mp 112–114°C), and a brown powder (mp 153–155°C) respectively. {Found for [(2-ABA) (2-NBA)]: C, 56.3; H, 4.1; N, 9.6%. Found for [(2-ABA) (3-NBA)]: C, 57.0; H, 4.0; N, 9.5%. $C_{14}H_{12}N_2O_6$ requires C, 55.3; H, 4.0; N, 9.2%. [(2-ABA) (2-NBA)]: *d(I/Io)* 3.75(100), 6.68(50), 6.28Å(20). [(2-ABA) (3-NBA)]: *d(I/Io)* 6.09(100), 5.08(80), 6.53Å(60). For 2-Aminobenzoic acid (2-ABA):α-form, *d(I/Io)* 3.66(100), 4.76(95), 6.44Å(60); **β**-form, *d(I/Io)* 5.84(100), 8.04(75), 4.03Å(70); **γ**-form, *d(I/Io)* 6.04(100), 7.66(50), 3.79Å(50). Attempts to prepare the 1:1 adducts of 2-ABA with 4-nitrobenzoic acid, and DNBA yielded powders consisting of both starting materials, which were identified using X-ray powder diffraction techniques.

[5] For 3-aminobenzoic acid with 2-nitrobenzoic acid [(3-ABA) (2-NBA)], and 3-nitrobenzoic acid [(3-ABA) (3-NBA)], the total evaporation of ethanol at room temperature yielded: yellow-brown plate-like needles (mp 143–145°C), and a light brown powder (mp 163–165°C) respectively. {Found for [(3-ABA) (2-NBA)]: C, 56.3; H, 4.0; N, 9.6%. Found for [(3-ABA) (3-NBA)]: C, 57.0; H, 4.1; N, 9.5%. $C_{14}H_{12}N_2O_6$ requires C, 55.3; H, 4.0; N, 9.3%}. [(3-ABA) (2-NBA)]: *d(I/Io)* 4.49(100), 5.31(98), 3.73Å(85). [(3-ABA) (3-NBA)]: *d(I/Io)* 3.66(100), 3.41(98), 3.22Å(95). 3-Aminobenzoic acid (3-ABA): *d(I/Io)* 5.20(100), 3.41(70), 3.31Å(60). Weissenberg photographs for [(3-ABA) (2-NBA)] indicated crystal twinning. However, the space group was determined as $P2_12_12_1$, with approximate cell dimensions a = 7.0, b = 12.4, c = 17.1Å V 1484Å^3, $Dc(Z = 4)$ 1.36 g cm^{-3} (M_r = 304.1), Dm <1.50 g cm^{-3} ($CHCl_3$). Attempts to prepare the 1:1 adduct of 3-ABA with 4-nitrobenzoic acid, yielded a powder consisting of both starting materials, which were identified using X-ray powder diffraction techniques.

Table 2. Atomic coordinates ($\times 10^4$) and equivalent isotropic thermal parameters (Å^2, $\times 10^3$) U_{eq} is defined as one third of the orthogonalized U_{ij} tensor

(1)

	x	y	z	U(eq)
C (1A)	4659 (10)	4510 (2)	2833 (6)	48 (1)
C (2A)	5035 (12)	4071 (2)	2962 (6)	52 (1)
C (3A)	6791 (12)	3856 (2)	2073 (7)	55 (2)
C (4A)	8252 (10)	4071 (2)	981 (6)	49 (1)
C (5A)	7871 (11)	4509 (2)	833 (6)	52 (1)
C (6A)	6123 (11)	4723 (2)	1739 (6)	51 (1)
C (11A)	2707 (10)	4726 (2)	3783 (6)	47 (1)
O (10A)	1493 (8)	4541 (1)	4802 (4)	60 (1)
O (11A)	2353 (8)	5136 (1)	3486 (5)	61 (1)
N (41A)	9883 (11)	3849 (2)	16 (6)	60 (1)
C (1B)	3348 (11)	3565 (2)	7059 (6)	53 (1)
C (2B)	1160 (12)	3479 (2)	5990 (6)	57 (2)
C (3B)	278 (14)	3073 (2)	5746 (7)	68 (2)
C (4B)	1566 (13)	2739 (2)	6542 (7)	59 (2)
C (5B)	3678 (13)	2815 (2)	7603 (8)	63 (2)
C (6B)	4594 (14)	3224 (2)	7869 (8)	62 (2)
N (11B)	4210 (14)	3980 (2)	7351 (7)	68 (2)
N (40B)	647 (15)	2300 (2)	6265 (8)	87 (2)
O (40B)	1866 (14)	2005 (2)	6921 (7)	115 (2)
O (41B)	−1343 (15)	2246 (2)	5340 (8)	129 (2)

(2)

	x	y	z	U(eq)
C (1A)	2349 (4)	2381 (2)	4809 (3)	55 (1)
C (2A)	1516 (4)	2562 (2)	4006 (3)	60 (1)
C (3A)	907 (4)	2025 (3)	3435 (3)	60 (1)
C (4A)	1110 (4)	1269 (2)	3645 (3)	54 (1)
N (41A)	509 (5)	729 (3)	3073 (3)	78 (1)
C (5A)	1941 (4)	1087 (2)	4447 (3)	58 (1)
C (6A)	2540 (4)	1631 (3)	5013 (3)	59 (1)
O (10A)	3685 (4)	2826 (2)	6148 (2)	80 (1)
O (11A)	2752 (4)	3642 (2)	5122 (2)	86 (1)
C (11A)	2995 (5)	2958 (3)	5434 (4)	64 (1)
C (1B)	2793 (4)	6649 (2)	172 (3)	52 (1)
C (11B)	2253 (5)	6072 (3)	−459 (3)	62 (1)
O (10B)	1535 (4)	6190 (2)	−1174 (2)	77 (1)
O (11B)	2629 (3)	5388 (2)	−199 (2)	85 (1)
C (2B)	2431 (4)	7392 (3)	4 (3)	58 (1)
C (3B)	2878 (4)	7939 (2)	600 (3)	58 (1)
C (4B)	3760 (4)	7774 (2)	1398 (3)	57 (1)
N (41B)	4191 (5)	8320 (3)	1994 (3)	73 (1)
C (5B)	4136 (4)	7037 (3)	1562 (3)	60 (1)
C (6B)	3673 (4)	6495(2)	964(3)	60(1)
N (1C)	3398 (5)	−131 (2)	1300 (3)	83 (1)
C (11C)	2570 (4)	2540 (2)	297 (3)	60 (1)
C (2C)	2368 (6)	249 (3)	1447 (4)	86 (2)
C (21C)	3842 (5)	2776 (2)	190 (3)	65 (1)
C (3C)	1837 (5)	878 (3)	999 (3)	76 (1)
C (31C)	4417 (5)	3416 (2)	562 (3)	64 (1)
C (4C)	2434 (4)	1145 (2)	355 (3)	60 (1)
C (41C)	3732 (4)	3828 (2)	1060 (3)	50 (1)
N (41C)	4334 (4)	4514 (2)	1463 (2)	64 (1)

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Table 2. Continued.

O (40C)	3804 (4)	4828 (2)	1972 (2)	86 (1)
O (41C)	5369 (3)	4743 (2)	1272 (2)	87 (1)
C (5C)	3506 (5)	745 (3)	196 (3)	71 (1)
C (51C)	2503 (4)	3601 (2)	1200 (3)	61 (1)
C (6C)	3955 (5)	122 (3)	674 (4)	82 (1)
C (61C)	1929 (4)	2957 (3)	816 (3)	68 (1)
C (7C)	1907 (5)	1841 (2)	−130 (3)	80 (2)
N (1D)	1164 (5)	9196 (3)	3820 (3)	90 (1)
C (11D)	2559 (4)	6546 (2)	4682 (3)	58 (1)
C (2D)	708 (6)	8834 (3)	4417 (4)	86 (2)
C (21D)	1383 (5)	6247 (3)	4848 (3)	70 (1)
C (3D)	1292 (5)	8231 (2)	4853 (3)	66 (1)
C (31D)	826 (5)	5587 (2)	4455 (3)	67 (1)
C (4D)	2489 (4)	7951 (2)	4675 (3)	56 (1)
C (41D)	1484 (4)	5246 (2)	3899 (2)	51 (1)
N (41D)	922 (4)	4544 (2)	3492 (2)	62 (1)
O (40D)	1493 (4)	4258 (2)	2967 (2)	80 (1)
O (41D)	−74 (3)	4277 (2)	3695 (2)	83 (1)
C (5D)	2996 (5)	8308 (3)	4055 (3)	77 (1)
C (51D)	2637 (4)	5531 (2)	3705 (3)	61 (1)
C (6D)	2301 (6)	8926 (3)	3656 (3)	91 (2)
C (61D)	3173 (4)	6195 (3)	4105 (3)	64 (1)
C (7D)	3158 (5)	7260 (2)	5127 (3)	73 (1)
N (1E)	3614 (5)	4806 (2)	6146 (2)	74 (1)
C (11E)	4548 (4)	7413 (3)	7433 (2)	52 (1)
C (2E)	4728 (5)	5203 (3)	6138 (3)	72 (1)
C (21E)	3388 (4)	7821 (2)	7450 (3)	58 (1)
C (3E)	5135 (5)	5810 (3)	6669 (3)	68 (1)
C (31E)	3145 (4)	8507 (2)	7056 (3)	59 (1)
C (4E)	4359 (4)	6026 (2)	7230 (3)	54 (1)
C (41E)	4083 (4)	8784 (2)	6635 (3)	52 (1)
N (41E)	3822 (4)	9506 (2)	6198 (2)	69 (1)
O (40E)	4498 (4)	9677 (2)	5687 (2)	105 (1)
O (41E)	2931 (5)	9904 (2)	6359 (3)	112 (1)
C (5E)	3215 (5)	5626 (3)	7227 (3)	77 (1)
C (51E)	5251 (4)	8408 (3)	6604 (3)	62 (1)
C (6E)	2877 (5)	5031 (3)	6674 (3)	90 (2)
C (61E)	5484 (4)	7728 (3)	7009 (3)	62 (1)
C (7E)	4783 (5)	6657 (3)	7856 (3)	64 (1)
N (1F)	1752 (4)	14220 (2)	8799 (3)	73 (1)
C (11F)	337 (4)	11605 (3)	7605 (3)	57 (1)
C (2F)	2456 (5)	13863 (3)	8319 (3)	83 (1)
C (21F)	1426 (4)	11162 (2)	7535 (3)	61 (1)
C (3F)	1998 (5)	13264 (3)	7812 (3)	74 (1)
C (31F)	1634 (4)	10480 (3)	7944 (3)	60 (1)
C (4F)	706 (5)	12998 (2)	7762 (3)	58 (1)
C (41F)	741 (4)	10253 (2)	8425 (3)	54 (1)
N (41F)	979 (4)	9521 (2)	8862 (2)	71 (1)
O (40F)	1731 (5)	9082 (2)	8635 (3)	111 (1)
O (41F)	407 (4)	9403 (2)	9443 (2)	101 (1)
C (5F)	−15 (5)	13349 (3)	8281 (3)	71 (1)
C (51F)	−371 (4)	10674 (3)	8505 (3)	63 (1)
C (6F)	524 (6)	13946 (3)	8769 (3)	81 (2)
C (61F)	−554 (4)	11356 (3)	8082 (3)	66 (1)
C (7F)	144 (5)	12353 (3)	7169 (3)	75 (1)

Table 2. Continued.

	(3)			
	x	y	z	U (eq)
C(1A)	6211(5)	1254(13)	7169(5)	56(2)
C(2A)	6621(6)	2212(16)	7943(5)	61(2)
C(3A)	6619(6)	1121(16)	8640(5)	65(2)
C(4A)	6211(5)	−985(15)	8609(5)	64(2)
C(5A)	5801(6)	−1973(15)	7839(6)	63(2)
C(6A)	5807(5)	−883(14)	7140(5)	60(2)
C(11A)	6213(5)	2510(15)	6441(4)	57(2)
O(10A)	6624(4)	4292(10)	6469(3)	74(2)
O(11A)	5738(4)	1513(11)	5739(4)	80(2)
N(41A)	6209(8)	−2038(19)	9309(7)	97(3)
C(1B)	6301(5)	5965(14)	13069(4)	57(2)
C(2B)	5868(6)	6903(15)	12298(5)	61(2)
C(3B)	5864(5)	5849(14)	11584(5)	57(2)
C(4B)	6307(5)	3774(13)	11652(4)	52(2)
C(5B)	6746(5)	2780(16)	12392(5)	61(2)
C(6B)	6750(5)	3918(15)	13097(5)	63(2)
C(11B)	6357(7)	7231(16)	13835(5)	64(2)
C(21B)	6254(6)	5832(15)	14518(5)	63(2)
O(20B)	5834(4)	4052(11)	14436(3)	82(2)
O(21B)	6651(5)	6754(11)	15229(3)	86(2)
N(40B)	6307(5)	2618(14)	10899(4)	71(2)
O(40B)	5975(5)	3562(11)	10239(3)	100(2)
O(41B)	6650(5)	757(12)	10958(4)	97(2)

(together with its 2- and 3-substituted isomers) form hetero-dimers both with Lewis bases and benzoic acids having acceptor substituent groups, although if proton transfer occurs, the resulting association involving the carboxylic acid group is via only one hydrogen bond. With complexes **3–8**, for which the evidence indicates the formation of hetero-dimers, the p*Ka* of the carboxylic acid group of the acceptor-substituted benzoic acid is either approximately equal to or greater than the p*Ka* of the carboxylic acid group of the corresponding amino-substituted benzoic acid. For examples known to form proton transfer complexes, the p*Ka* of the acceptor-benzoic acid is either approximately equal to or less than the p*Ka* of the corresponding amino-benzoic acid. Comparative p*Ka* values for each species in both heterodimer and proton transfer complexes are given in Table 3. In complexes of acids with approximately equal p*Ka* values, steric factors and competing hydrogen bonding systems may also be important in controlling the process of structure making.

Of the ten adducts of 4-ABA which are known or probable heterodimers, the crystallographic space groups for only three are known, {[(4-ABA) (4-NPA)] ($P2_1/a$), [(4-ABA) (2-CPAA)] ($P2_1/c$) (both centrosymmetric) and [(4-ABA) (DNBA)] (*Fdd2*) (non-

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Table 3. Comparative p*K*a values, space groups and observed SHG for the donor and acceptor species in both heterodimer and proton transfer complexes in aminobenzoic acid cocrystals

	p*K*a	Space group	SHG	Reference
Heterodimer Complex				
[(4-ABA) (DNBA)]	2.38, 2.82	*Fdd2*	+	3
[(4-ABA) (2-CPA)]	2.38, 2.50	$P2_1/c$	−	6
[(4-ABA) (4-NPA)]	2.38, 3.85	$P2_1/a$	−	This work **3**
[(4-ABA) (4-CBA)]	2.38, 3.98	*	−	This work **4**
[(4-ABA) (4-BBA)]	2.38, 3.97	*	−	This work **5**
[(4-ABA) (4-CNBA)]	2.38, 3.55	*	−	This work **6**
[(4-ABA) (2-NBA)]	2.38, 2.22	*	−	This work **7**
[(4-ABA) (3-NBA)]	2.38, 3.44	*	−	This work **8**
[(2-ABA) (2-NBA)]	2.05, 2.22	*	−	This work
[(2-ABA) (3-NBA)]	2.05, 3.44	*	−	This work
Proton Transfer Complex				
$[(4\text{-ABA})^+ (PDCA)^-]$	2.38, 2.27[3]	$P2_1/c$	−	7
$[(4\text{-ABA})^+ (TNBA)^- (H_2O)]$	2.38, 0.65	*Pbcn*	−	8
$[(4\text{-ABA}) (4\text{-ABA})^+ (DNSA)^-]$	2.38, 2.14	$P\bar{1}$	−	9
$[(3\text{-ABA})^+ (2\text{-NBA})^-]$	3.07, 2.22	$P2_12_12_1$	−	This work
$[(3\text{-ABA})^+ (3\text{-NBA})^-]$	3.07, 3.44	*	−	
$[(3\text{-ABA})^+ (DNBA)^-]$	3.07, 2.82	$P\bar{1}$	−	30
[(3-ABA) (DNBA) $(3\text{-ABA})^+ (DNBA)^- (H_2O)$]	3.07, 2.82	$P2_12_12_1$	+	30

* not known

[3] pKa_1 for pyrazine-2, 3-dicarboxylic acid. $pKa_2 = 4.63$.

centrosymmetric)}. The available structural information on the remaining seven gives no indication of the nature of the packing arrays expected or the possibility of molecular asymmetry existing. However, preliminary qualitative second harmonic generation tests were carried out on powdered samples of all listed compounds {except [(4-ABA) (DNBA)]} as a check for possible noncentrosymmetric packing. Although no quantitative optical measurements were possible a strong SHG signal, evident as a visible green glow

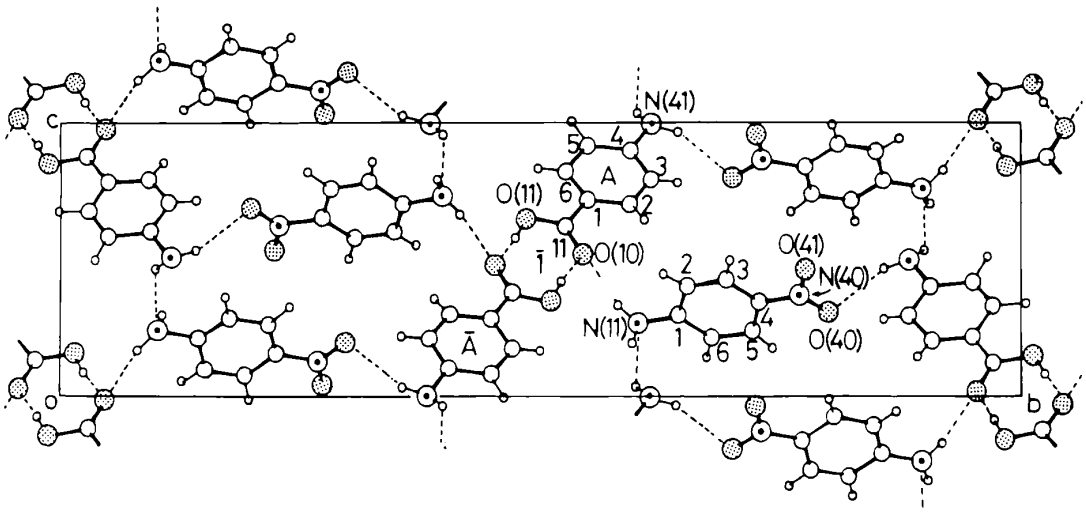

Fig. 1. Packing of **1** in the unit cell showing atom numbering scheme. Unless otherwise indicated, atoms are carbon. In all figures, for clarity, only those molecules involved in hydrogen bonding interactions (broken lines) are shown.

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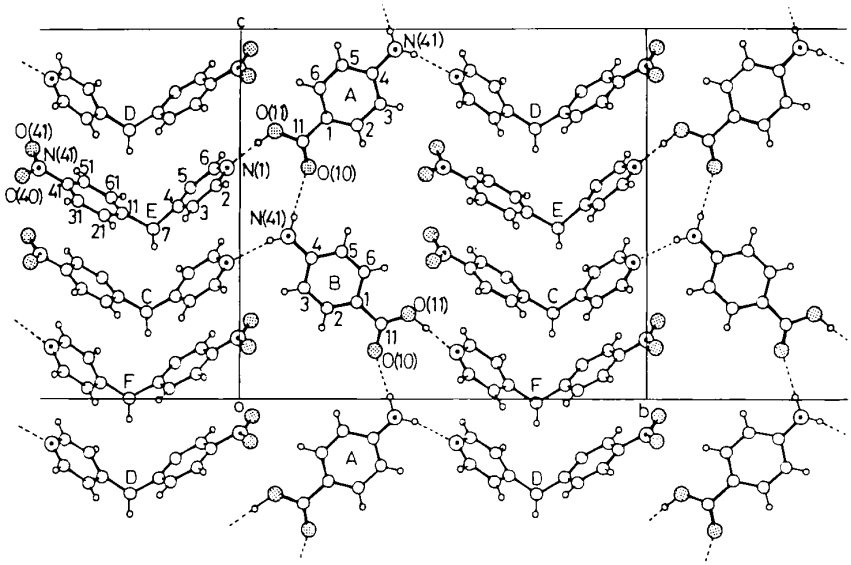

Fig. 2. Packing of **2** in the unit cell.

(532nm) from the sample upon irradiation with the Nd:YAG laser source (1064nm) indicates an active compound. These tests confirm that of the heterodimer complexes listed, only [(4-ABA) (DNBA)] is optically active. Of the seven compounds known to be proton transfer complexes, four {[(4-ABA)$^+$ (PDCA)$^-$], [(4-ABA)$^+$ (TNBA)$^-$ (H_2O)], [(4-ABA) (4-ABA)$^+$ (DNSA)$^-$], and [(3-ABA)$^+$ (DNBA)$^-$]} are centrosymmetric, two are noncentrosymmetric {[(3-ABA)$^+$ (2-NBA)$^-$] and [(3-ABA) (DNBA) (3-ABA)$^+$ (DNBA)$^-$ (H_2O)]}, while for (3-ABA)$^+$ (3-NBA)$^-$], the space group is unknown. However, of these only [(3-ABA) (DNBA) (3-ABA)$^+$ (DNBA)$^-$ (H_2O)] displayed any visible SHG signal.

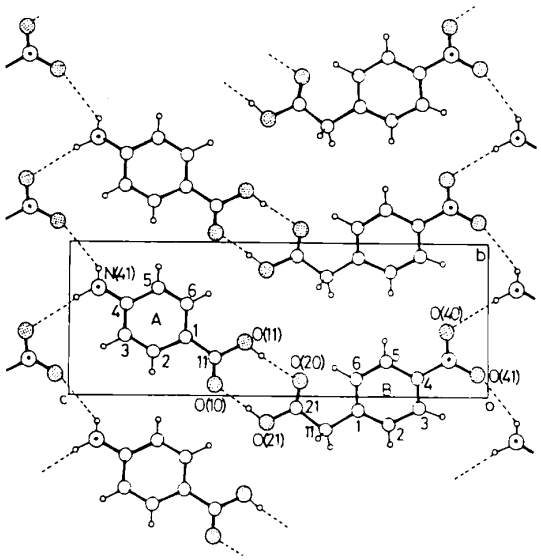

Fig. 3. Packing of **3** in the unit cell.

Conclusions

The structures of a relatively large set of 4-aminobenzoic acid adducts with nitro-substituted aromatic compounds have provided a set of data which enables the more accurate description of the characteristics of the possible interactions. Two basic interactions are possible, the first and most common involving no proton transfer, the second, occurring with the stronger carboxylic acids results in proton transfer to the amino group of 4-ABA. Such proton transfer interactions result in the disruption of the process proposed by Etter[22,23] which leads to possible formation of the linear arrays required for acentric packing. However, such interactions do aid in adduct formation, as well as generally increasing the thermal stability of the subsequent crystals, and as has been observed in the series reported here, still allows formation of optically active noncentrosymmetric crystal lattices. With those processes involving no proton transfer, the primary molec-

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ular association results, in the majority of cases in a cyclic hydrogen bonded A-A dimer with the A-B heterodimer associations less prevalent or predictable. Also, in most examples, the natural packing of either homo- or heterodimers of 4-ABA (or carboxylic acids generally) is centric, with rare acentric examples, these being potentially useful optically. In all cases, infrared spectroscopy may be used to recognize the nature of the association. However, prediction of the general outcome of the crystallisation process is not as yet a reality in the design of organic compounds with NLO properties.

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Supplementary material. Crystallographic data (excluding structure factors) for the structures reported in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC-1003/5157 (for **1**), CCDC-1003/5158 (for **2**), and CCDC-1003/5159 (for **3**). Copies of available material can be obtained, free of charge, on application to the Director, CCDC, 12 Union Road, Cambridge CB2 1EZ, UK, (fax: +44-(0)1223-336033 or e-mail: teched@chemcrys.cam.ac.uk).

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