Interchangeability of halogen and ethynyl substituents in the solid state structures of di- and tri-substituted benzenes†

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Examination of the solid state structures of bromo- and fluoro-substituted ethynylbenzenes, determined by single crystal X-ray diffraction, has demonstrated that the halogen and ethynyl substituents on these 1,4- and 1,3,5-substituted benzene rings can be interchanged without significant changes in their average solid state structures. Consideration of these structures, together with those of 1,4- and 1,3,5-substituted halogenobenzenes, suggests that, in most cases, shape complementarity may be of equal importance to interactional complementarity when attempting to rationalise the packing of these molecules in the solid state.

Introduction

The development of crystal engineering[1] relies on advancing our understanding of the factors that control the packing of molecules in the solid state. Fundamental to such theories is the rationalisation of the intermolecular forces found in the solid state—thus allowing elucidation of the criteria which control the dominance of one type of interaction over another, and the subtle interplay between different interactions of comparable influence. The prediction of hydrogen bonding patterns from the identification of recognition processes at a molecular level, such as the use[2] by Etter and Bernstein of graph-set analyses, has traditionally employed motifs based on conventional, strong intermolecular interactions such as O–H···O and N–H···O. However, for a complete understanding of the criteria which determine molecular packing, more subtle effects that contribute to the overall recognition properties of a molecular building block, such as shape, size and the role of very weak intermolecular interactions [such as π···π stacking,[3] C–H···π(Ar) interactions,[4] C–H···π(C≡C) interactions,[5] and X···X (where X is a halogen) interactions[6]] must also be rationalised. The effects of weaker hydrogen bonds on the crystal structure are evidently more subtle and therefore, in general, rationalisation of their importance in determining packing features presents a greater challenge. The rationalisation by Desiraju[1c,e] of the motif-forming characteristics of functional groups in terms of "supramolecular synthons" has been applied successfully, not only to stronger interaction motifs, such as amide and carboxylic acid dimers, but also to very weak interactions such as those involving aromatic–bromine[7] and nitro–iodo[8] contacts.

Recently, there has been much interest in X···X contacts, especially Cl···Cl and Br···Br. Analyses of crystal structures containing X···X distances close to, or less than, the sum of the van der Waals radii of the two halogen atoms have prompted the suggestion that a special attractive interaction can exist between halogen atoms. Statistical analyses[9] of Cl···Cl and Br···Br interactions have demonstrated that Br···Br interactions and, to a much lesser extent, Cl···Cl interactions prefer an orientation in which the axes of the two C–X bonds are perpendicular to each other. So far, it is unclear whether these close contacts are the result of an attractive charge-transfer or donor–acceptor type interaction between the halogen atoms or whether, in the case of chlorine, they can be attributed[10] to the anisotropy (*i.e.* non-spherical nature) of the halogen atom.

Another area of topical interest in this field concerns ≡C–H···π(C≡C) interactions between terminal alkynes. Unfortunately, most crystal structures containing such interactions also contain stronger hydrogen bonds (often O–H···O) as the dominant intermolecular interaction, obscuring the role of the ≡C–H···π(C≡C) interactions in influencing the structural properties. It is clear that studies of ≡C–H···π(C≡C) interactions should focus on structures in which much stronger interactions are absent. Recently, the crystal structures of ethynylbenzene (phenylacetylene), 1,4-diethynylbenzene and 1,3,5-triethynylbenzene have been determined,[11] and illustrate that, for a series of structures dictated by weak interactions, subtle differences in molecular structure can have a large impact on crystal structure. The crystal structure of ethynylbenzene is dominated by the ethynyl groups forming ≡C–H···π(Ar) interactions, whereas in 1,4-diethynylbenzene and 1,3,5-triethynylbenzene the alkyne residues participate only in ≡C–H···π(C≡C) interactions.

In this paper, we report the crystal structures, determined by single crystal X-ray diffraction, of several di- and tri-substituted benzenes containing ethynyl and halogen substituents. These structures are compared with the crystal structures of di- and tri-substituted halogenobenzenes and with the crystal structures of di- and tri-substituted ethynylbenzenes, leading to an overall understanding of the opportunities for interchanging halogens and ethynes in the crystal structures of these materials.

Results and discussion

Disubstituted benzenes

The crystal structure of 1-bromo-4-ethynylbenzene **1** (Fig. 1a) has been determined from single crystal X-ray diffraction data, as described in the Experimental section.‡ There are three molecules in the asymmetric unit related by an approximate

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† Full crystallographic details, excluding structure factor tables, have been deposited at the Cambridge Crystallographic Data Centre (CCDC). For details of the deposition scheme, see 'Instructions for Authors', *J. Chem. Soc.*, *Perkin Trans. 2*, available *via* the RSC Web page (http://www.rsc.org/authors). Any request to the CCDC for this material should quote the full literature citation and the reference number 188/142.

‡ During the preparation of this paper, Weiss *et al.* reported[13] the structure of 1-bromo-4-ethynylbenzene **1** at 125 K. The structure is very similar to that reported here, although it is not isomorphous; this may reflect the different crystal growth techniques employed (sublimation *vs.* slow evaporation of solvent) and the difference in the temperatures at which the diffraction experiments were performed (125 *vs.* 198 K).

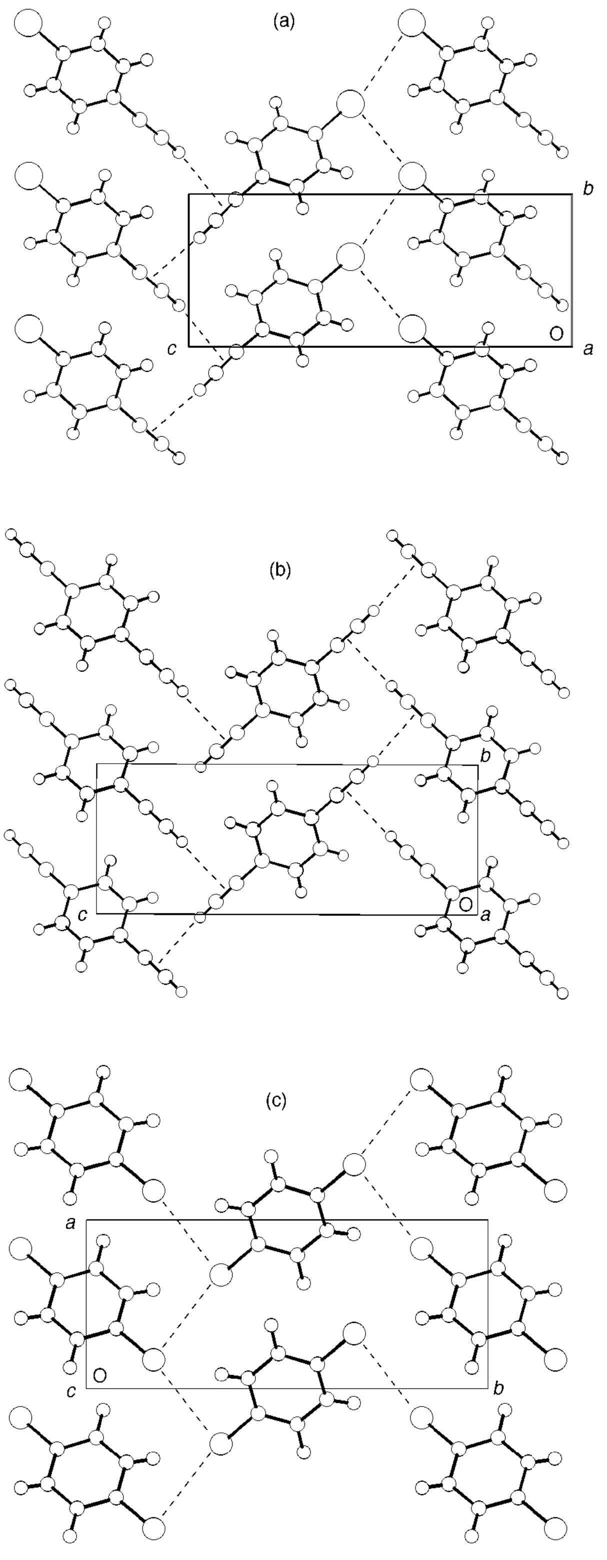


Fig. 1 Crystal structures of (a) 1-bromo-4-ethynylbenzene **1** viewed along the *a*-axis, (b) 1,4-diethynylbenzene **2** viewed along the *a*-axis and (c) the α form of 1,4-dichlorobenzene **4** viewed along the *c*-axis.

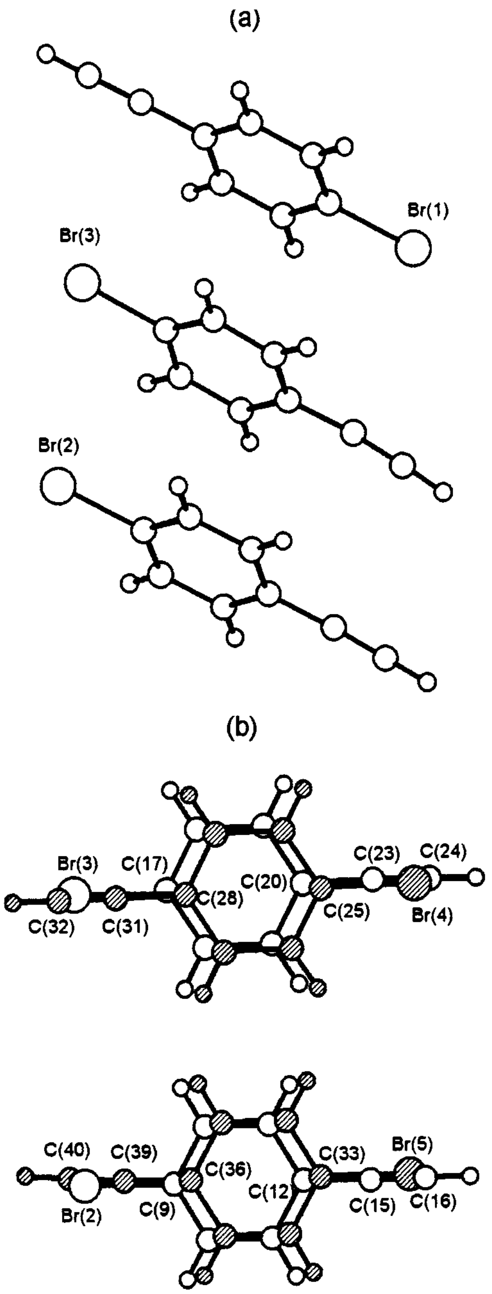
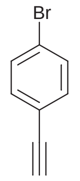


Fig. 2 Ball and stick representations of (a) the ABB type stacking in the structure of **1** found in the domains containing the major orientation, and (b) the disordered molecular orientations in the average crystal structure of **1**.

translation of *a*/3 along the *a*-axis. In the structure refinement, it was necessary to consider orientational disorder of these molecules, although significant disorder was found for only two of the molecular sites in the asymmetric unit. In this disorder, there are two molecular orientations (Fig. 2b) representing head–tail disorder of the bromo and ethynyl groups between the 1 and 4 positions on the benzene ring. The positions of the carbon atoms of the benzene ring are different in the two molecular orientations, with one molecule translated along the plane of the aromatic ring with respect to the other. For both disordered molecular sites, the occupancies of the two molecular orientations are almost equal—in one case the major orientation has a refined occupancy of 65%, whereas for the other case the major orientation has a refined occupancy of 63%. The type of head–tail disorder found for **1** is also commonly found for mixed 1,4-dihalogenobenzenes and other 1-halogeno-4-ethynylbenzenes [however, in contrast to the situation for **1**, the disorder in mixed 1,4-dihalogenobenzenes (such as 1-bromo-4-chlorobenzene[12] **3**) is such that the positions of the ring carbon atoms are the same for the two molecular orientations, and in most cases the two molecular orientations have equal (50%) occupancy].

For the other molecule in the asymmetric unit of **1**, no significant orientational disorder was found. As shown in Fig. 2, the orientation of the ordered molecule (defined as the orientation of the vector from the 1-substituent to the 4-substituent) is the opposite of the major orientations of the two disordered molecules. Thus, considering the major orientation of each molecular site, the structure has an ABB type stacking along



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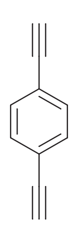

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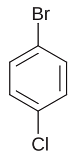

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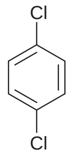

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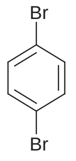

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the *a*-axis as shown in Fig. 2a. This represents the most probable type of ordered domain of this structure, and is consistent with an *a*-axis repeat involving three molecules (as found in the average crystal structure). As discussed below, each independent molecule in the asymmetric unit gives rise to a two-dimensional sheet structure; each sheet comprises only one of the three types of molecule in the asymmetric unit.

We now consider in more general terms the type of disorder found in the crystal structure of **1**; these general concepts are also relevant in considering the other crystal structures reported below. It is important to recall that crystal structure determination from X-ray diffraction data, as reported here, gives only an average representation of the structure, with the averaging carried out over all unit cells within the crystal. In the case of **1**, the average structure implies that there is disorder involving the orientations of the molecules in the crystal, although the exact nature of this disorder cannot necessarily be determined unambiguously from the diffraction data alone. In general, if an average crystal structure indicates that there is head–tail disorder of a molecule between two orientations X–Y (with occupancy x%) and Y–X [with occupancy $(100 - x)$%], we cannot deduce *a priori* whether the structure comprises: (a) ordered domains containing *only* the X–Y orientation (with x% of the crystal comprising this type of domain) and ordered domains containing *only* the Y–X orientation [with $(100 - x)$% of the crystal comprising this type of domain]; or (b) a situation in which, in each region of the crystal, each molecule has a statistical probability of being oriented as X–Y (with x% probability) or oriented as Y–X [with $(100 - x)$% probability]. In case (a), the molecular orientations within a given domain are ordered, and the disorder in the average structure arises from averaging over the different domains. In case (b), the disorder exists at the molecular level, and in principle the orientation of a given molecule should be uncorrelated with the orientations of its neighbours. Furthermore, this orientational disorder may be dynamic (with each molecule changing between the X–Y and Y–X orientations as a function of time) or static (with each molecule remaining in the same orientation as a function of time, the orientational disorder presumably having been "locked" into the crystal during crystal growth). Clearly for case (a), the molecules in the ordered domains have a well-defined set of interactions with their neighbours, and the local structure within a given domain should be analogous to that in a conventional ordered crystal structure. For case (b), on the other hand, a range of different local intermolecular environments may exist, depending on the orientation of a given molecule and the set of orientations of all its neighbours. Disorder of type (b) may in fact be precluded if some of the intermolecular interactions that would be predicted to exist, on a statistical basis, between a pair of neighbouring molecules are highly unfavourable. We shall refer to orientational disorder of type (a) as disorder involving ordered domains, and to orientational disorder of type (b) as statistical disorder of individual molecules.

We now assess whether the average crystal structure of **1** is consistent with disorder of types (a) and/or (b). In this case, statistical disorder of individual molecules would allow both $Br\cdots\pi(C\equiv C)$ and $C–H\cdots Br$ interactions to exist within each layer. However, for the $C–H\cdots Br$ interactions, the intermolecular distances would be significantly shorter than the sum of the van der Waals radii[§] ($d_{H\cdots Br} = 2.5$ to 2.6 Å, $\Sigma_{vdW} = 2.94$ Å), and we may propose that disorder of type (b) is highly unlikely to exist for **1**. Therefore, the crystal is likely to comprise ordered domains in which there are only $C–H\cdots\pi(C\equiv C)$ and $Br\cdots Br$ interactions. The two different ordered domains (each comprising just one orientation of the molecule) might both exist within a given layer [in which case the structure at the domain boundary represents an interesting issue (which cannot be assessed from diffraction data)], or it may be that each layer comprises only one type of ordered domain, and the disorder arises through "errors" in the stacking of layers. From the diffraction data discussed here, we cannot assess which of these situations is a more correct description of the present case.

We now consider in more detail the structure within an ordered domain of **1** (Fig. 1a). Within a layer of this structure, the terminal alkyne groups form chains of zigzag $C–H\cdots\pi(C\equiv C)$ contacts[¶] [$d_{H\cdots\pi(C\equiv)} = 2.7$ to 2.8 Å, where (C≡) represents one carbon atom of the C≡C bond, $\Sigma_{vdW} = 2.84$ Å], similar to those found in the crystal structure of 1,4-diethynylbenzene **2** (Fig. 1b). Additionally, $Br\cdots Br$ close approaches ($d_{Br\cdots Br} = 3.9$ to 4.0 Å, $\Sigma_{vdW} = 3.70$ Å) are formed within each layer. There are also $Br\cdots Br$ close approaches ($d_{Br\cdots Br} = 3.9$ to 4.1 Å) between layers.

The crystal structures of 1-halogeno-4-ethynylbenzenes recently reported[13] by Weiss *et al.*, for which the halogen is chlorine, bromine or iodine, are all isomorphous (space group $P2_1/c$) and have been shown to be remarkably similar to symmetrically and unsymmetrically substituted 1,4-dihalogenobenzenes such as **3**, the α form of 1,4-dichlorobenzene[14] **4** and 1,4-dibromobenzene[15] **5**, which are themselves isomorphous (space group $P2_1/a$). The 1-bromo-4-ethynylbenzene phase reported here has a different space group ($P2_1$) and a different disorder model to that reported by Weiss *et al.*,[||] but the overall packing arrangement of the $P2_1$ phase is essentially the same as that found in the structures of **2**–**5** and any of the 1-halogeno-4-ethynylbenzenes (Fig. 1, Tables 1 and 2).

Infra-red spectroscopy has been used extensively to analyse weak interactions, such as $C–H\cdots O$[16] and $C–H\cdots\pi(C\equiv C)$,[5] in the solid state. In principle, the $C–H\cdots\pi(C\equiv C)$ interaction weakens the C–H bond and thus shifts the alkyne C–H stretching vibration to a lower frequency. The difference (denoted $\Delta\nu_{\equiv C–H}$) between the "free" alkyne C–H stretching frequency (ν_1) determined for a solution of **2** in CCl_4 and the alkyne C–H stretching frequency (ν_2) in the solid gives a qualitative indication of the strength of these weak interactions in the solid state. There is strong evidence that this approach is sufficiently sensitive to distinguish different $C–H\cdots\pi(C\equiv C)$ intermolecular interaction environments. For example, the

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[§] Surprisingly, the characterisation of intermolecular contacts in crystal structures is normally based upon tabulations of van der Waals radii dating back over 30 years (A. Bondi, *J. Phys. Chem.*, 1964, **68**, 441). A recent re-evaluation of these distances (R. S. Rowland and R. Taylor, *J. Phys. Chem.*, 1996, **100**, 7384) showed good agreement with the data of Bondi in most cases. All the van der Waals distances used in this paper use the normalised *R* radii values obtained by Rowland and Taylor.

[¶] We have recently demonstrated (D. Philp and J. M. A. Robinson, *J. Chem. Soc.*, *Perkin Trans. 2*, 1998, 1643) that the potential energy surface for the $C\equiv C–H\cdots\pi(C\equiv C)$ interaction between terminal alkynes is relatively insensitive to the position of the hydrogen atom along the C≡C bond vector. Therefore, in this paper, we have characterised these interactions as the intermolecular distance from the alkyne proton to the nearest of the two carbon atoms of the triple bond *i.e.* $C\equiv C–H\cdots\pi(C\equiv)$.

[||] The $P2_1/c$ structure of **1** reported by Weiss *et al.*[11a] contains only one type of (disordered) molecule. The molecule has two molecular orientations (with equal occupancies) displaying head–tail disorder between the bromo and ethynyl sites. Additionally, the positions of the carbon atoms of the benzene ring in the two molecular orientations are translated with respect to one another. This type of disorder is comparable with the disorder seen in two of the three molecules in the asymmetric unit of the $P2_1$ phase.

Table 1 Crystallographic data of the structures studied in the present work

	Compound			
	1	**8**	**9**	**11**
Formula	C_8H_5Br	$C_8H_4Br_2$	$C_{10}H_5Br$	$C_{10}H_5F$
M_w/g mol^{-1}	181.03	259.930	205.05	144.14
Melting point/°C	63.5–64.5	107.0–108.0	108.5–109.0	66.0–66.5
Temperature/K	198(2)	295(2)	263(2)	243(2)
Crystal system	Monoclinic	Orthorhombic	Orthorhombic	Orthorhombic
Space group	$P2_1$	$P2_12_12_1$	$P2_12_12_1$	$P2_12_12_1$
a/Å	11.9382(6)	13.853(6)	13.879(3)	13.427(3)
b/Å	5.8966(3)	14.744(7)	14.867(3)	14.781(7)
c/Å	15.6656(9)	4.036(2)	4.0642(3)	3.7843(4)
β/°	109.120(4)	90.00	90.00	90.00
Cell volume/Å^3	1041.94(10)	824.4(6)	838.6(3)	751.0(2)
Z	6	4	4	4
Crystal size/mm^3	0.30 × 0.30 × 0.05	0.50 × 0.10 × 0.05	0.10 × 0.10 × 0.05	0.50 × 0.10 × 0.08
Measured reflections	5895	3260	4860	3896
Unique reflections	3261	1166	1439	1244
Unique refl. [for $F^2 > 2\sigma(F^2)$]	2146	924	1412	1002
Goodness of fit	1.057	1.148	1.162	1.175
$wR(F^2)$ [for $F^2 > 2\sigma(F^2)$]	0.140	0.156	0.097	0.125
R [for $F^2 > 2\sigma(F^2)$]	0.057	0.071	0.042	0.061

Table 2 Selected crystallographic data of di- and trisubstituted ethynyl- and halogeno-benzenes for comparison with the structures of **1**, **8**, **9** and **11**

	Compound					
	2[a]	**4**[b]	**5**[c]	**12**[d]	**13**[d]	**14**[a]
Formula	$C_{10}H_6$	$C_6H_4Cl_2$	$C_6H_4Br_2$	$C_6H_3Cl_3$	$C_6H_3Br_3$	$C_{12}H_6$
Melting point/°C	94.5–95.5	54–56	87–88	63–65	121–124	104–105
Temperature/K	295(2)	100	293	295	295	295(2)
Crystal system	Monoclinic	Monoclinic	Monoclinic	Orthorhombic	Orthorhombic	Monoclinic
Space group	$P2_1/c$	$P2_1/a$	$P2_1/a$	$P2_12_12_1$	$P2_12_12_1$	$C2/c$
a/Å	3.967(2)	14.664	15.491(4)	13.930	14.230	19.0968(3)
b/Å	5.992(4)	5.740	5.828(3)	13.190	13.550	4.0525(3)
c/Å	15.169(8)	3.925	4.102(3)	3.91	4.080	23.815(3)
β/°	91.199(14)	111.77	112.95(3)	90	90	108.096(2)
Z	2	2	2	4	4	8
R [for $F^2 > 2\sigma(F^2)$]	0.058	0.050	0.061	0.084	0.095	0.055

[a] Data from ref. 11*b*. [b] Data from ref. 14. [c] Data from ref. 15. [d] Data from ref. 18.

Table 3 Infra-red alkyne C–H stretching frequencies (cm^{-1})

Compound	$\nu_{\equiv\text{C–H}}$ (CCl_4)	$\nu_{\equiv\text{C–H}}$ (KBr)	$\Delta\nu_{\equiv\text{C–H}}$
1	3312	3261	51
2	3307	3262	45
8	3304	3284	20
9	3308	3284	24
11	3309	3301	8
		3291	18
14	3309	3296	13
		3279	30

three crystallographically inequivalent C–H···π(C≡C) interactions in the crystal structure of ethynylferrocene have been attributed[5c] to the three C–H stretching frequencies observed in the infra-red spectrum.

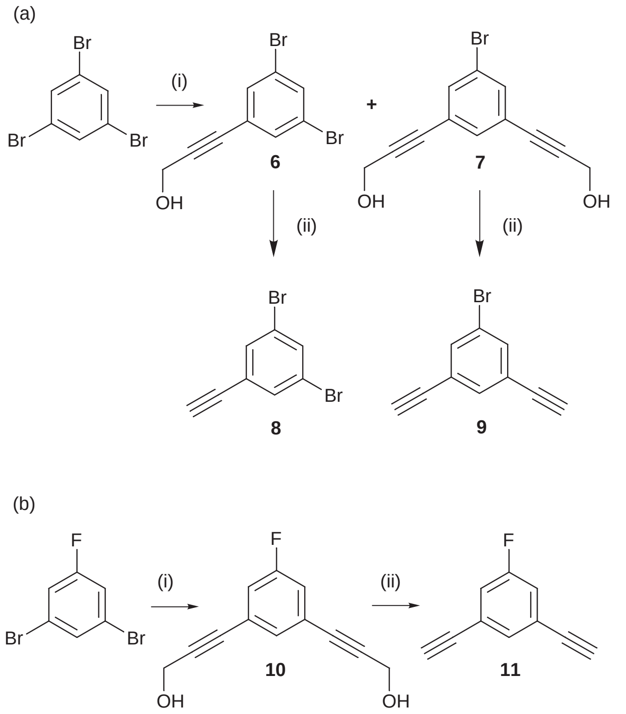
The infra-red spectrum of the $P2_1$ phase of **1** contains only one strong signal in the alkyne C–H stretching region, which is red-shifted (*i.e.* negative $\Delta\nu_{\equiv\text{C–H}}$) with respect to the C–H stretching frequency in solution by 51 cm^{-1} (Table 3). This shift can be attributed to a C–H···*a* interaction (where *a* is any hydrogen bond acceptor), and almost certainly represents a C–H···π(C≡C) close contact. For comparison, we have also measured the infra-red spectra of 1,4-diethynylbenzene **2** in the crystalline and solution states. The crystal structure contains only one type of C–H···π(C≡C) interaction (H···M distance 2.68 Å, where M is the midpoint of the triple bond, C–H···M angle, 176.1°). In this case, $\Delta\nu_{\equiv\text{C–H}}$ is 45 cm^{-1}. The lack of any other C–H stretching bands in the infra-red spectrum of **1** lends weight to the hypothesis that the crystal contains predominantly domains or layers in which there are only C–H···π(C≡C) and Br···Br interactions. On the other hand, if C–H···Br interactions were also present, they would result in a smaller $\Delta\nu_{\equiv\text{C–H}}$.

Trisubstituted benzenes

In order to extend further our understanding of intermolecular interactions in benzenes substituted with ethynyl and halogen substituents, we have also synthesised and determined the crystal structures of several trisubstituted 1,3,5-ethynylhalogenobenzenes.

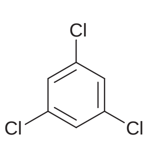
The synthesis of aromatic systems substituted with terminal alkynes is normally achieved by the Pd-catalysed cross-coupling of trimethylsilylacetylene with halogenobenzenes followed by cleavage of the trimethylsilyl protecting group under basic conditions. However, we have adopted an alternative synthesis[17] of terminal alkynes that utilises successive oxidation and decarboxylation of prop-2-yn-1-ols, and thus avoids the use of expensive and highly volatile trimethylsilylacetylene.

The Pd-catalysed cross-coupling of 1,3,5-tribromobenzene with 2.5 equivalents of propargyl alcohol (prop-2-yn-1-ol) afforded a mixture of monosubstituted and disubstituted products (Scheme 1) which were separable by column chromatography. The oxidation of the respective mono- and bis(prop-2-yn-1-ol)s, **6** and **7** with MnO_2 under basic conditions afforded the respective alkynes **8** and **9** *via* the carboxylate intermediates. The synthesis of 1-fluoro-3,5-diethynylbenzene **11** was accomplished using identical methodology.



Scheme 1 (i) Propargyl alcohol, $PdCl_2$, PPh_3, $Cu(OAc)_2$, $^{i}Pr_2NH$. (ii) MnO_2, KOH, CH_2Cl_2.

1,3-Dibromo-5-ethynylbenzene 8. In the crystal structure of **8** (Fig. 3a), molecules are arranged in a layered structure, which is isomorphous to 1,3,5-trichlorobenzene[18] **12** and 1,3,5-tribromobenzene[18] **13** (Fig. 3b). The asymmetric unit contains one molecule, and it is found that there is orientational disorder of the $C_8H_4Br_2$ molecule (Fig. 4a). Specifically, the $C_8H_4Br_2$ molecules adopt three orientations, representing disorder of the bromine and ethynyl substituents among three sites corresponding to the 1, 3 and 5 positions on the benzene ring; the positions of the carbon atoms of the benzene ring in the three molecular orientations are indistinguishable. The relative occupancies of the three molecular orientations are 65, 25 and 10%. We now assess whether the average crystal structure of **8** is consistent with disorder of types (a) and/or (b) discussed above. In this case, statistical disorder of individual molecules would give rise to H···H close approaches significantly shorter than the sum of the van der Waals radii ($d_{H\cdots H}$ = 1.82 Å, Σ_{vdW} = 2.18 Å). Thus, as in the case of **1**, the structure is likely to comprise ordered domains, rather than statistical disorder of individual molecules.



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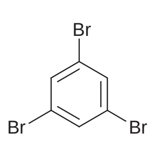

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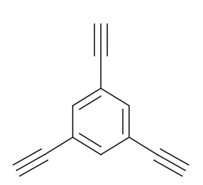

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The structure contains no significant C–H···π(C≡C) contacts although a domain comprising only the minor (10%) molecular orientation would contain a very short C–H···Br contact ($d_{H\cdots Br}$ = 2.46 Å, Σ_{vdW} = 2.94 Å). For each of the molecular orientations, there are several short Br···Br close approaches, whose Br···Br separation is close to the sum of the van der Waals radii ($d_{Br\cdots Br}$ = 3.87–4.00 Å, Σ_{vdW} = 3.70 Å).

The infrared spectrum of **8** shows a $\Delta\nu_{\equiv C-H}$ shift of 20 cm^{-1}, which presumably arises from the C–H···Br interactions and the weak C–H···π(C≡C) interactions. In comparison, the infra-red spectrum of crystalline 1,3,5-triethynylbenzene **14** shows two distinct peaks in the C–H stretching region. The $\Delta\nu_{\equiv C-H}$ values (Table 3) are consistent with the nature[11] of the C–H···π(C≡C) interactions in the crystal structure of **14**, for which there are three different C–H···π(C≡C) environments; the shortest ($d_{H\cdots\pi(C\equiv)}$ = 2.60 Å) could be attributed to the 30 cm^{-1} shift whereas the other two ($d_{H\cdots\pi(C\equiv)}$ = 2.80 and 2.96 Å) could be attributed to the 13 cm^{-1} shift.

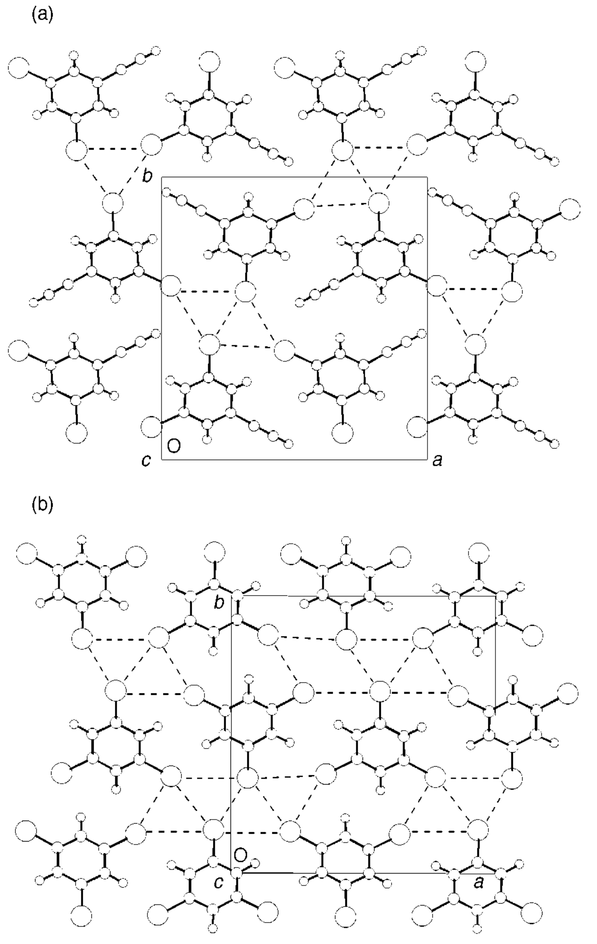

Fig. 3 Crystal structures of (a) 1,3-dibromo-5-ethynylbenzene **8** (showing only the major molecular orientation) and (b) 1,3,5-tribromobenzene **13**, viewed along the *c*-axis in both cases. Note that the interactions represented by dotted lines do not necessarily interconnect molecules within the same "layer".

1-Bromo-3,5-diethynylbenzene 9. The crystal structure of **9** is isomorphous with the structure of **8**, with nearly identical unit cell dimensions (Table 1). There is one molecule in the asymmetric unit. Again, there is orientational disorder of the $C_{10}H_5Br$ molecules (Fig. 4b), with three orientations corresponding to disorder of the bromine and ethynyl substituents among the three sites corresponding to the 1, 3 and 5 positions on the benzene ring; the positions of the carbon atoms of the benzene ring in the three molecular orientations are indistinguishable. The occupancies of the three molecular orientations are 86, 7 and 7%. Unlike the structures of **1** and **8**, however, we cannot rule out the possibility that this structure has statistical disorder of individual molecules. The structure contains close H···H and H···Br approaches which are shorter than the sum of the van der Waals radii ($d_{H\cdots H}$ = 2.08 Å, $d_{H\cdots Br}$ = 2.81 Å), but as these occur only for the two minor (7%) molecular orientations (with their neighbours also in the minor orientations) it is probable that the overall structure can have statistical disorder of individual molecules. Several Br···Br close approaches are close to the sum of the van der Waals radii (Br···Br distances 3.88 and 4.08 Å). The structure also contains C–H···π(C≡C) interactions (shortest $d_{H\cdots\pi(C\equiv)}$ = 2.50 Å) which are presumably represented in the infra-red

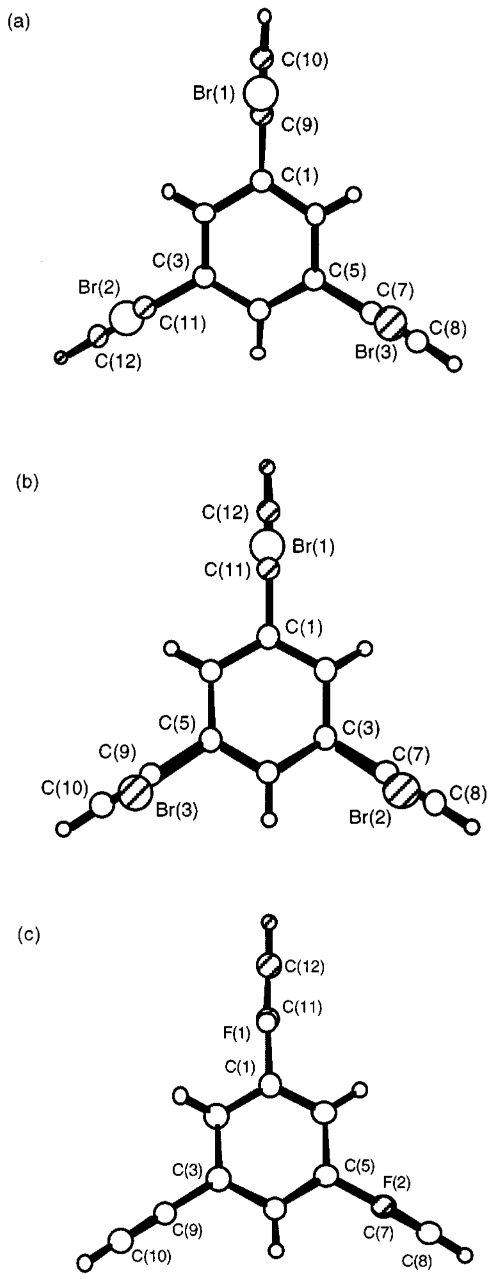

Fig. 4 Ball and stick representation of the disordered molecular orientations in the average crystal structures of (a) **8**, (b) **9** and (c) **11**. The open and shaded circles represent the different components of the disordered structure.

spectrum by a $\Delta\nu_{\equiv C-H}$ shift of 24 cm^{-1} (Table 3). In summary, from knowledge of the average crystal structure of **9** from diffraction data, we cannot deduce in this case whether the disorder is more likely to be of type (a) or type (b).

1-Fluoro-3,5-diethynylbenzene 11. The crystal structure of **11** (Fig. 5) is also isomorphous with the structures of **8** and **9**. However, unlike the situation for **8** and **9**, the $C_{10}H_5F$ molecules in the average crystal structure of **11** adopt only two orientations, corresponding to disorder of the fluorine and one ethynyl substituent between two sites. The position of the other ethynyl group is ordered, and the positions of the carbon atoms of the benzene ring in the two molecular orientations are indistinguishable. The occupancies of the two molecular orientations are 63 and 37%. In this case, statistical disorder of individual molecules would give rise to a H···H close contact of only 0.95 Å, and we may therefore conclude that the disorder is more likely to comprise two types of ordered domains, as shown in Fig. 6.

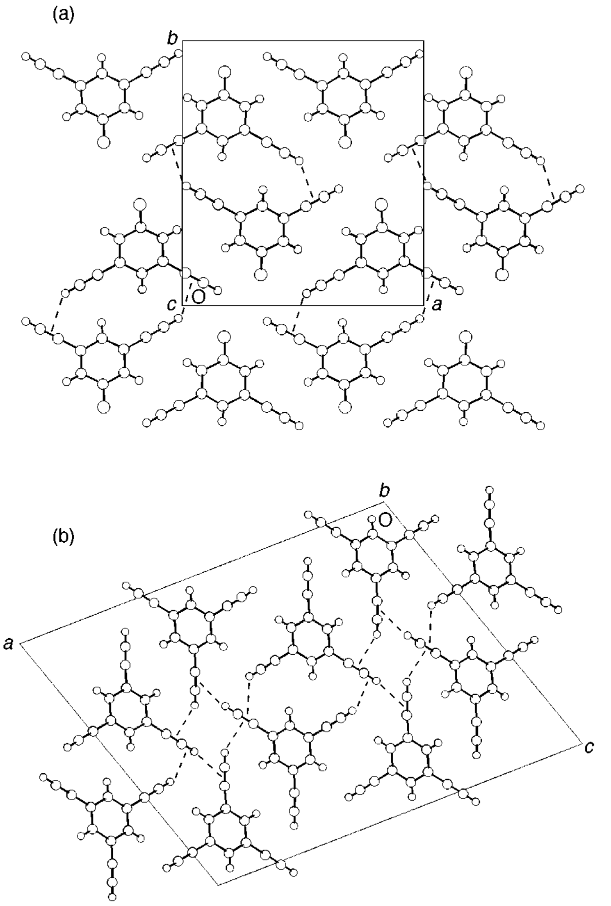

Fig. 5 Crystal structures of (a) 1-fluoro-3,5-diethynylbenzene **11** (showing only the major molecular orientation) viewed along the *c*-axis and (b) 1,3,5-triethynylbenzene **13** viewed along the *b*-axis. Note that the interactions represented by dotted lines do not necessarily interconnect molecules within the same "layer".

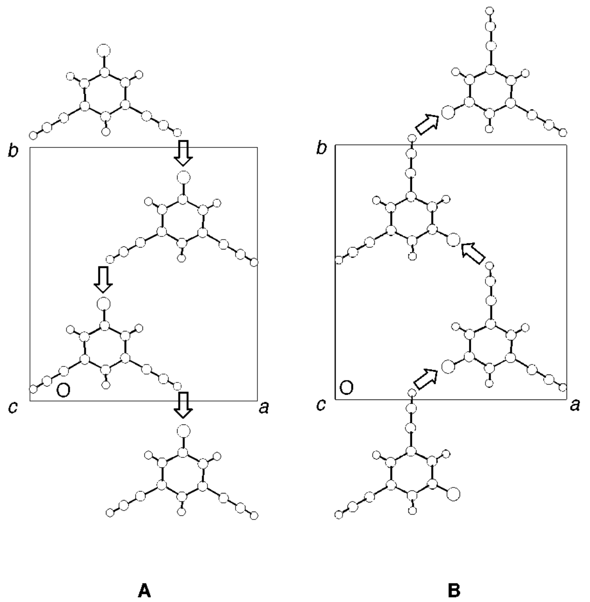

Fig. 6 Views of the different ordered domains that are proposed to exist in the crystal structure of **11**. The directions of the arrows which follow the C–H···F close approaches emphasise the differences between the domains.

In either domain, the shortest C–H···π(C≡C) contact is 2.69 Å. Although fluorine is an electronegative atom, it is generally regarded to be a poor hydrogen bond acceptor, especially in the case of C–H···F interactions.[11a,19] The structure contains some C–H···F close approaches ($d_{H\cdots F}$ = 2.89–2.91 Å, Σ_{vdW} =

2.53 Å) although the absence of any significant C–H···F interactions is evident from the fact that the observed $\Delta\nu_{\equiv C\text{–}H}$ shifts (8 and 18 cm^{-1}) in the infra-red spectrum are small. As far as we are aware, the 8 cm^{-1} shift is one of the smallest $\Delta\nu_{\equiv C\text{–}H}$ shifts yet reported, and supports the assertion that infra-red spectroscopy is a useful means for probing the strength of intermolecular interactions (an ethynyl group engaged in a very weak intermolecular interaction is expected to have a correspondingly small $\Delta\nu_{\equiv C\text{–}H}$ shift).

Discussion

The average crystal structures of the 1,3,5-trisubstituted compounds **8**, **9** and **11** are isomorphous with 1,3,5-trichlorobenzene **12** and 1,3,5-tribromobenzene **13**. In particular, in the average crystal structures, the positions of the halogen atoms and ethynyl groups can be essentially superimposed, and we discuss this issue further (see below) in the light of the known orientational disorder in these materials. The 1,4-disubstituted compounds **1**–**5** are not all isomorphous, although they do have very similar structures.

In rationalising the crystal structures of the 1,4-disubstituted and 1,3,5-trisubstituted benzenes discussed here, it is clearly important to assess and understand the observed orientational disorder of the molecules. In particular, to assess questions such as the possible interchangeability of ethynyl groups and halogens in these structures, we must understand the nature of the disorder at the local molecular level, rather than simply considering the average crystal structure determined from diffraction data. As discussed above, the types of orientational disorder observed in the average crystal structures reported here may be consistent, in principle, with either of the following extreme situations: (a) the crystal comprises different ordered domains (with strong correlations between the orientations of a given molecule and its neighbours), or (b) the crystal has statistical disorder in the orientations of all individual molecules (with no strong correlations between the orientations of a given molecule and its neighbours). Clearly intermediate situations between the extremes (a) and (b) may be envisaged. Close analysis of the structures suggests that, in most cases, situation (b) would lead to specific unfavourable interactions between neighbouring molecules within a layer, suggesting that situation (a) [or an intermediate situation lying close to (a)] is a more correct description of the disorder in these systems.

In order to assess the "interchangeability" of halogen and ethynyl substituents in crystal structures of the type reported here, it is clearly essential for us to understand in detail the nature of the disorder in these structures. Extreme situation (a) should be expected to arise when there is significant discrimination in terms of the interactions (halogen···halogen; ethynyl···ethynyl; halogen···ethynyl) formed within a given layer, leading to ordered domains. However, from the information presently available we cannot comment on whether, for situation (a), each layer in the structure comprises only one type of domain (with the disorder arising only through disorder in the stacking of these ordered layers) or whether the different ordered domains exist within each individual layer. In the former case, the disorder would originate through indiscrimination of the π···π stacking between layers rather than indiscrimination in the interactions formed between molecules within the layer. When disorder is described by situation (a), rationalisation of structures requires us to understand the preferred intermolecular interactions giving rise to the ordered domains. In order to understand why the different domains can co-exist requires us to understand, *inter alia*, the structural nature of the boundaries between the different domains.

Extreme situation (b), on the other hand, should be expected to arise when there is almost no discrimination in terms of the interactions formed within a given layer and presumably also in terms of the interactions formed between adjacent layers. For this situation, it would be valid to consider that there is more-or-less complete interchangeability of halogen and ethynyl substituents in the packing of these molecules.

Table 4 Molecular volumes

Substituent[a]	Volume/Å^3	Compound	Volume/Å^3
Ar–F	6.9	C_8H_5Br **1**	159.7
Ar–Cl	18.1	$C_{10}H_6$ **2**	164.1
Ar–Br	24.4	$C_6H_4Cl_2$ **4**	142.5
Ar–C_2H	28.8	$C_6H_4Br_2$ **5**	155.2
		$C_8H_4Br_2$ **8**	184.1
		$C_{10}H_5Br$ **9**	188.5
		$C_{10}H_5F$ **11**	171.0
		$C_6H_3Cl_3$ **12**	160.6
		$C_6H_3Br_3$ **13**	179.6
		$C_{12}H_6$ **14**	192.9

[a] Molecular volume of an individual group X (X = F, Cl, Br or C_2H) when attached to a phenyl ring calculated as the difference between the molecular volume of *Ar*–X and the molecular volume of benzene.

As discussed above, there is evidence to suggest that the disorder in the structures of **1**, **8** and **11** cannot be described as situation (b), although a full characterisation and understanding of this issue will require the application of a range of techniques that probe the local structural properties, as opposed to the average structural properties revealed by diffraction-based methods. In the light of this situation, it is nevertheless relevant to discuss some general issues concerning the packing of molecules in the crystal structures of 1,4-disubstituted and 1,3,5-trisubstituted benzenes, as these issues play an important role in governing the disorder. In particular, disorder may be expected to arise when there is compatibility of the *molecular volumes* and/or the *molecular recognition characteristics* of the different molecular orientations involved in the disorder. In this regard, the same issues are relevant in relation to extreme situations (a) and (b), where in the former case the compatibility of the different molecular orientations at the boundaries between domains is a crucial factor governing the disorder, whereas in the latter case the compatibility of the different molecular orientations at each molecular site in the crystal is crucial. We now consider in more detail specific aspects of the molecular volumes and molecular recognition characteristics for the specific molecules of interest here.

Molecular volumes. The volumes of the 1,4-disubstituted and 1,3,5-trisubstituted benzenes discussed above have been calculated using the molecular geometries obtained from semiempirical AM1 calculations** (Table 4). The volume of an individual atom or group Y (where Y = F, Cl, Br or C_2H) bonded to a phenyl ring was estimated as the difference between the molecular volume of Ph–Y (Ph = phenyl) and the molecular volume of benzene. Although there is a large variation in these volumes for the different substituents considered [only bromine (24.4 Å^3) is comparable to C_2H (28.8 Å^3)], the overall volumes within each set of 1,4-disubstituted and 1,3,5-trisubstituted benzenes are relatively similar. Unfortunately, very few crystal structures have been reported for disubstituted and trisubstituted benzenes bearing functional groups of similar volumes to those discussed here. The overall packing in the structure[20] of *p*-xylene [for which the calculated volume (147.2 Å^3) is comparable with **4**] resembles that for the 1,4-disubstituted benzenes described above. However, the structure of *p*-xylene is not superimposable on the structure of **4** (there are significant differences in the angles of tilt of the molecules with respect to each other).

** Semiempirical optimisations and the calculation of the molecular volumes of CPK-type models were performed using SPARTAN (Wavefunction, Inc., 18401 Von Karman Suite 370, Irvine, CA 92612, USA, 1997, Version 5.0.3).

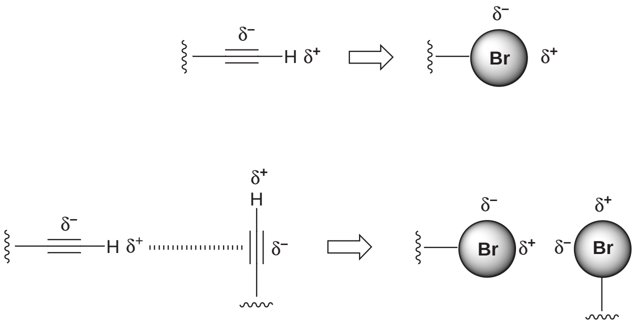

Fig. 7 Comparison of the polarisation patterns found in terminal alkynes with that for halogens.

Molecular recognition characteristics. Analysis[9b] of the orientation of the C–X···X–C bonds in halogen–halogen interactions has indicated that one of the halogens acts as a nucleophile whereas the other acts as an electrophile. The approach of the axis of one C–X bond is often approximately perpendicular to the axis of the other C–X bond, and presumably results from the X atoms being polarised δ(+) in the polar region (along the C–X axis) and δ(−) in the equatorial region. This polarisation pattern is similar to that for terminal alkynes, which are also polarised δ(+) in the polar region (along the C–H axis) and δ(−) in the equatorial region (the triple bond), as shown in Fig. 7. Thus (see Fig. 7), the geometrical characteristics of the preferred approach of one halogen towards another in X···X interactions are markedly similar to those of the preferred approach of C–H towards C≡C in C–H···π(C≡C) interactions.

In the structures considered here, the disorder involves different molecular orientations for which only the positions of inequivalent substituents are interchanged. In this regard, all the structures within a given class have a remarkably similar *overall packing* of the molecules. We now assess this issue in more detail. Thus, in terms of the overall molecular packing, the *average structures* of the 1,4-disubstituted benzenes considered here may be rationalised in terms of a molecular building block with pseudo D_{2h} symmetry, and the *average structures* of the 1,3,5-trisubstituted benzenes may be rationalised in terms of a molecular building block with pseudo D_{3h} symmetry. In this regard, we are not assessing whether there is order or disorder in terms of the specific interactions between the substituents [as this underpins the distinction between disorder of types (a) and (b) discussed above], but rather we are considering the overall orientation of the molecules. In this description, the average crystal structures of the 1,3,5-trisubstituted compounds **8**, **9**, **11**, **12** and **13** may be represented by a triangular cartoon (Fig. 8a) which can be tessellated to form stacks of parallel "ribbons". The stacks arise from $\pi\cdots\pi$ interactions [we note that all the structures have similar offsets (1.82–2.07 Å) of the aromatic rings between adjacent layers except **11** (1.33 Å)]. Within each layer, the molecules in adjacent ribbons interdigitate with one another, presumably to maximise van der Waals attractions [which may be more dominant than the X···X and C–H···π(C≡C) interactions that control the packing within each layer]. In a similar manner, the average structures of the 1,4-disubstituted compounds **1**–**4** can be represented by the tessellation of rectangles of D_{2h} symmetry, as shown in Fig. 8b. The extension of this picture of overall molecular packing to include a description of the actual interactions between molecules in the crystal (*i.e.* the assignment of substituents to the triangular or rectangular building blocks) clearly requires specific knowledge of the nature of the disorder in the structure.

The above contention that the packing within the layers of the 1,4-disubstituted and 1,3,5-trisubstituted benzenes is dictated primarily by molecular shape rather than the establishment of specific intermolecular interactions may suggest, at first sight, that the Br···Br and Cl···Cl close approaches in these structures do not constitute significant interactions. Indeed, the shortest Cl···Cl close approaches are not actually shorter than the sum of the van der Waals radii [disubstituted (**4**), $d_{\mathrm{Cl}\cdots\mathrm{Cl}} = 3.81$ Å; trisubstituted (**12**) $d_{\mathrm{Cl}\cdots\mathrm{Cl}} = 3.63$ Å; $\Sigma_{\mathrm{vdW}} = 3.48$ Å]. This observation is also true for the shortest Br···Br close approaches [disubstituted (**5**) $d_{\mathrm{Br}\cdots\mathrm{Br}} = 3.81$; trisubstituted (**13**) $d_{\mathrm{Br}\cdots\mathrm{Br}} = 3.76$ Å; $\Sigma_{\mathrm{vdW}} = 3.70$ Å]. Nevertheless, close approaches that are comparable to, although slightly longer than, the sum of the van der Waals radii may still constitute a significant attractive intermolecular interaction (although perhaps relatively weak).

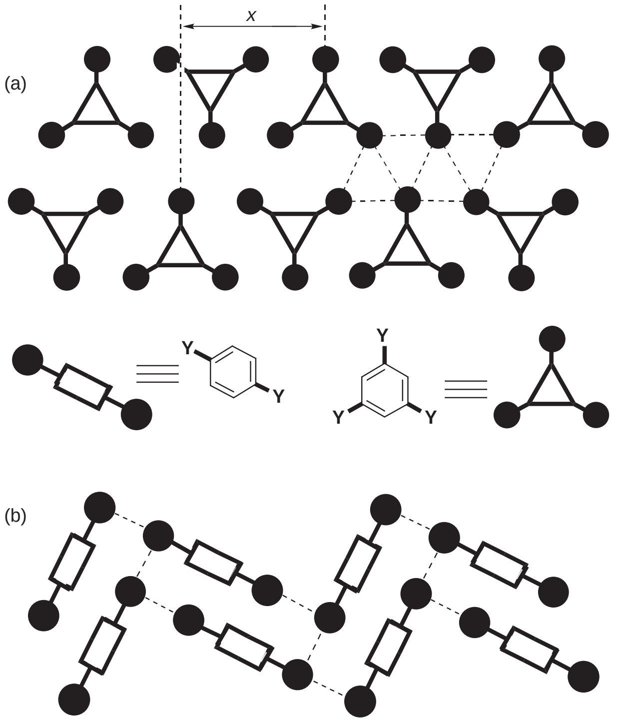

Fig. 8 Representation of the crystal structures of (a) trisubstituted 1,3,5-halogenoethynylbenzenes and 1,3,5-trihalogenobenzenes using triangular cartoons and (b) 1,4-disubstituted halogenoethynylbenzenes, dihalogenobenzenes and diethynylbenzenes using rectangular cartoons. The distance *x* represents the slippage of one molecular "ribbon" with respect to the adjacent ribbon, with the resulting interdigitation maximising the van der Waals contacts.

There are two notable exceptions that do not share the packing charactersitics of the 1,4-di- and 1,3,5-trisubstituted benzenes discussed above. Firstly, the crystal structure (monoclinic, *C*2/*c*) of 1,3,5-triethynylbenzene **14** is quite different from the structures (orthorhombic, $P2_12_12_1$) of the 1,3,5-trihalogenobenzenes and 1,3,5-trisubstituted benzenes containing both halogen and ethynyl substituents. It is clear that the shape of the 1,3,5-triethynylbenzene molecule, in comparison with analogous molecules containing one or more halogen substituents, allows 1,3,5-triethynylbenzene to adopt a structure involving greater interpenetration of the substituents with maximisation of the C–H···π(C≡C) contacts. Secondly, the packing of molecules in the crystal structure[13] of 1-fluoro-4-ethynylbenzene is totally different to that observed for the other 1-halogeno-4-ethynylbenzenes (where halogen = Cl, Br or I). The structure of 1-fluoro-4-ethynylbenzene is dominated by ≡C–H···F interactions as compared to the C–H···π(C≡C) interactions present in the structure of the other halogenoethynylbenzenes.

Finally, we note that the crystal structures of the corresponding monosubstituted benzenes could offer insights into the role of the types of intermolecular interactions discussed above. However, no structures of monohalogenobenzenes have yet been reported. On the other hand, the structure of ethynylbenzene (phenylacetylene) **15** is known,[11a] and contains both C–H···π(C≡C) and edge-to-face-type C–H···π(Ar) interactions. Thus, the crystal structure of **15** exhibits a compromise between the herringbone packing of benzene and the π···π coplanar stacking found in the 1,4-disubstituted and 1,3,5-trisubstituted benzenes discussed above. The mixture of C–H···π(C≡C) and (presumably weaker) C–H···π(Ar) interactions represents a less efficient packing, as a result of which **15** has an unusually low melting point (50 °C lower than that of benzene).

Experimental

General

Diisopropylamine was purified by refluxing with sodium hydroxide pellets under a N_2 atmosphere and was collected by distillation. All other solvents and reagents were used as received. Activated manganese(IV) dioxide (<5 micron, 85% purity) was supplied by Aldrich. Thin layer chromatography (TLC) was performed on aluminium plates coated with Merck Kieselgel 60 F_{254} and scrutinised under a UV lamp. Column chromatography was performed using Kieselgel 60 (0.040–0.063 mm mesh, Merck 9385). Melting points were determined using an Electrothermal 9200 melting point apparatus and are uncorrected. ^{1}H Nuclear Magnetic Resonance (NMR) spectra were recorded on a Bruker AC300 (300.1 MHz) spectrometer using the deuterated solvent as the lock and the residual solvent as the internal reference. ^{13}C NMR spectra were recorded on a Bruker AC300 (75.5 MHz) spectrometer using the PENDANT sequence. Chemical shifts are given in ppm and *J* values in Hz. Electron impact mass spectrometry (EIMS) and high resolution mass spectrometry were carried out on a VG PROSPEC mass spectrometer.

Synthetic procedures

1-Bromo-4-ethynylbenzene (1). Copper(II) acetate dihydrate (362 mg, 2 mmol), PPh_3 (1.05 g, 4 mmol) and $PdCl_2$ (354 mg, 2 mmol) were added to a stirred solution of 1,4-dibromobenzene (9.44 g, 40 mmol) in diisopropylamine (100 mL). The mixture was degassed by bubbling a fast stream of N_2 gas through the solution and warming to about 50 °C to dissolve the solids. Upon cooling to room temperature, propargyl alcohol (5.38 g, 96 mmol) was added in small portions during one hour after which time the mixture was refluxed for 3 h. Upon cooling, the colloidal palladium solids were removed by suction filtration, and the filtrate was evaporated under vacuum affording a mixture of 1-bromo-4-(3-hydroxyprop-1-ynyl)benzene and 1,4-bis(3-hydroxyprop-1-ynyl)benzene as a brown oil. Activated manganese(IV) oxide (34.78 g, 400 mmol) and potassium hydroxide (11.22 g, 200 mmol) were added to a stirred solution of this residue in a CH_2Cl_2–Et_2O mixture (200 mL, v:v 3:1). After 90 minutes, the solids were removed by filtration, the filtrate evaporated under vacuum, and the resulting light-brown powder partitioned between water (25 mL) and CH_2Cl_2 (50 mL). The organic layer was dried ($MgSO_4$) and evaporated under vacuum. The products were separated by column chromatography (SiO_2; hexanes) to afford 1,4-diethynylbenzene (1.110 g, 22%) and **1** (0.504 g, 7%) as colourless powders. *Data for* **1**; mp 63.5–64.5 °C (Lit.[21] 64 °C); δ_H (300 MHz; $CDCl_3$; Me_4Si) 3.12 (1 H, s), 7.32–7.36 (2 H, m), 7.43–7.47 (2 H, m); δ_C (75 MHz; CD_3COCD_3; Me_4Si) 78.33, 82.53, 120.98, 123.10, 131.56, 133.51; *m*/*z* 180 (M^+, 7%), 182 ([$M^+ + 2$], 6).

1,3-Dibromo-5-(3-hydroxyprop-1-ynyl)benzene (6) and 1-bromo-3,5-bis(3-hydroxyprop-1-ynyl)benzene (7). Copper(II) acetate dihydrate (182 mg, 1 mmol), PPh_3 (525 mg, 2 mmol) and $PdCl_2$ (177 mg, 1 mmol) were added to a stirred solution of 1,3,5-tribromobenzene (6.296 g, 20 mmol) in diisopropylamine (100 mL). The mixture was degassed by bubbling a fast stream of N_2 gas through it and warmed to about 50 °C to dissolve the solids. Upon cooling to room temperature, propargyl alcohol (2.47 g, 44 mmol, 2.2 equiv.) was added in small portions during 20 minutes after which time the mixture was heated at 50 °C for 2.5 h. Upon cooling, the colloidal palladium solids were removed by suction filtration, and the filtrate was evaporated under vacuum. The residual oil was taken up in CH_2Cl_2 (100 mL), washed with 5% HCl solution (30 mL) and brine (2 × 30 mL), dried ($MgSO_4$) and evaporated under vacuum. The resulting oil was purified by column chromatography (SiO_2; CH_2Cl_2–Et_2O, v:v 1:1) to afford three fractions: unreacted 1,3,5-tribromobenzene (0.524 g, 8%), **6** (0.617 g, 11%) and **7** (2.789 g, 53%).

Data for **6**; mp 88.0–88.5 °C; δ_H (300 MHz; $CDCl_3$; Me_4Si) 2.51 (1H, s), 4.47 (2H, s), 7.46 (2H, d, *J* 1.5), 7.58–7.59 (1 H, t, *J* 1.5); δ_C (75 MHz; CD_3COCD_3; Me_4Si) 50.77, 81.49, 92.92, 123.26, 127.61, 133.68, 134.54; *m*/*z* (HR) found, 287.8787; $C_9H_6Br_2O$ (M^+) requires 287.8785.

Data for **7**; mp 107.5–108.5 °C; δ_H (300 MHz; CD_3COCD_3; Me_4Si) 4.40–4.47 (6H, m), 7.40–7.41 (1H, t, *J* 1.5), 7.56 (2H, d, *J* 1.5); δ_C (75 MHz; CD_3COCD_3; Me_4Si) 50.85, 82.21, 92.07, 122.45, 126.18, 133.60, 134.44; *m*/*z* 265 (M^+, 80%), 267 ([$M^+ + 2$], 78) (Found: C, 54.47; H, 3.48. $C_{12}H_9BrO_2$ requires C, 54.37; H, 3.42%).

1,3-Dibromo-5-ethynylbenzene (8). Activated manganese(IV) oxide (1.800 g, 20 mmol) and potassium hydroxide (0.561 g, 10 mmol) were added to a stirred solution of **6** (580 mg, 2 mmol) in CH_2Cl_2 (25 mL). After 45 minutes, the solids were removed by filtration, and the filtrate evaporated under vacuum affording **8** as a tan coloured powder (520 mg, 90%), mp 107.0–108.0 °C; δ_H (300 MHz; $CDCl_3$; Me_4Si) 3.16 (1H, s), 7.54–7.55 (2H, d, *J* 1.5), 7.64–7.65 (1H, t, *J* 1.5); δ_C (75 MHz; $CDCl_3$; Me_4Si) 79.93, 80.65, 122.64, 125.49, 133.61, 134.69; *m*/*z* (HR) found, 259.8669; $C_8H_4Br_2$ (M^+) requires 259.8653.

1-Bromo-3,5-diethynylbenzene (9). Activated manganese(IV) oxide (6.560 g, 75.6 mmol) and potassium hydroxide (2.117 g, 37.8 mmol) were added to a stirred solution of **7** (1.00 g, 3.78 mmol) in CH_2Cl_2 (50 mL). After 16 h, the solids were removed by filtration, and the filtrate evaporated under vacuum affording **9** as off-white crystals (514 mg, 67%), mp 108.5–109.0 °C; δ_H (300 MHz; $CDCl_3$; Me_4Si) 3.13 (2H, s), 7.51–7.52 (1H, t, *J* 1.5), 7.56–7.59 (2H, d, *J* 1.5); δ_C (75 MHz; $CDCl_3$; Me_4Si) 79.17, 80.98, 121.67, 123.98, 134.05, 134.97; *m*/*z* (HR) found, 205.9563; $C_{10}H_5Br$ (M^+) requires 205.9554.

1-Fluoro-3,5-bis(3-hydroxyprop-1-ynyl)benzene (10). Copper(II) acetate dihydrate (91 mg, 0.5 mmol), PPh_3 (262 mg, 1 mmol) and $PdCl_2$ (89 mg, 0.5 mmol) were added to a stirred solution of 1,3-bromo-5-fluorobenzene (2.539 g, 10 mmol) in diisopropylamine (40 mL). The mixture was degassed by bubbling a fast stream of N_2 gas through it and warmed to about 50 °C to dissolve the solids. Upon cooling to room temperature, propargyl alcohol (1.344 g, 24 mmol) was added in small portions during one hour after which time the mixture was heated at reflux temperature for 2 h. Upon cooling, the colloidal palladium solids were removed by suction filtration, and the filtrate was evaporated under vacuum. The residual oil was taken up in CH_2Cl_2 (50 mL), washed with 5% HCl solution (30 mL) and water (2 × 30 mL), dried ($MgSO_4$) and evaporated under vacuum. The resulting oil was purified by column chromatography (SiO_2; CH_2Cl_2–Et_2O, v:v 1:1) to afford **10** as a tan coloured powder (1.608 g, 79%), mp 108.0–108.5 °C; δ_H (300 MHz; CD_3COCD_3; Me_4Si) 4.40–4.44 (6H, m), 7.20–7.16 (2H, dd, *J* 9.2, 1.0), 7.26 (2H, t, *J* 1.0); δ_C (75 MHz; CD_3COCD_3; Me_4Si) 52.26, 82.47, 91.67, 118.71, 119.01, 126.12, 126.26, 131.12, 161.20, 164.46; *m*/*z* 204 (M^+, 100%) (Found: C, 70.60; H, 4.57. $C_{12}H_9FO_2$ requires C, 70.58; H, 4.44%).

1-Fluoro-3,5-diethynylbenzene (11). Activated manganese(IV) oxide (6.079 g, 20 mmol) and potassium hydroxide (1.962 g, 10 mmol) were added to a stirred solution of **10** (715 mg, 3.5 mmol) in a mixture of CH_2Cl_2 (50 mL) and Et_2O (30 mL). After 2.5 hours, the solids were removed by filtration, and the filtrate evaporated under vacuum affording **11** as off-white crystals (347 mg, 69%), mp 66.0–66.5 °C; δ_H (300 MHz; $CDCl_3$; Me_4Si) 3.12 (2H, s), 7.14–7.18 (2H, dd, *J* 8.5, 1.0), 7.38–7.39 (1H, t, *J* 1.0); δ_C (75 MHz; $CDCl_3$; Me_4Si) 79.16, 81.61, 119.65, 119.96, 124.29, 124.42, 131.89, 160.31, 163.59; *m*/*z* (HR) found, 144.0380; $C_{10}H_5F$ (M^+) requires 144.0375.

Infra-red spectroscopy

Infra-red spectra were recorded on a Perkin Elmer Paragon 1000 FTIR spectrometer at ambient temperatures. Solid-state spectra were obtained as pressed KBr disks. The possibility of polymorphic interference—induced by the pressing of the KBr disk—could not be discounted since the compounds were appreciably soluble in the commonly used mulls (Nujol and hexachlorobuta-1,3-diene). Solution spectra were recorded at a concentration of approximately 2 mM in CCl_4 in an Aldrich Demountable liquid-cell kit with a pathlength of 0.5 mm. In each case, 32 scans of spectral range 4400 to 440 cm^{-1} at 2 cm^{-1} resolution were averaged.

Single crystal X-ray diffraction

All single crystal X-ray diffraction experiments were carried out using graphite-monochromated MoKα radiation ($\lambda = 0.71069$ Å) on a Rigaku R-Axis II diffractometer equipped with an area detector and a rotating anode source. All structures were solved and refined by standard methods (TEXSAN,[22] SHELXL93[23]). Terminal alkyne C–H bond lengths were normalised at 1.06 Å in accordance with neutron diffraction studies. In all cases, attempts at refining the structures on the basis of racemic twinning did not improve the structure solutions.

Crystals of C_8H_5Br (**1**) were grown by slow evaporation of solvent from a solution of **1** in a methanol–water mixture. The crystals are susceptible to sublimation, and single crystal X-ray diffraction data were recorded at low temperature (198 K). Information relating to the data collection, unit cell determination and space group assignment are summarised in Table 1. There are three independent molecules in the asymmetric unit (space group $P2_1$ with $Z = 6$). From the direct methods structure solution calculation and subsequent difference Fourier analysis, most non-hydrogen atoms were located. It was clear that there is orientational disorder for two of the C_8H_5Br molecules within the asymmetric unit, with no evidence for disorder of the other C_8H_5Br molecule. For each of the two disordered cases, the C_8H_5Br molecule adopts two orientations, representing "head–tail" disorder of the bromine and ethynyl substituents between sites corresponding to the 1 and 4 positions on the benzene ring. The positions of the carbon atoms of the benzene ring for the two molecular orientations are different. The occupancies of the two molecular orientations were refined (subject to the total occupancy for the site equalling 100%), leading to occupancies of 65 and 35% for one disordered molecular site, and 63 and 37% for the other disordered molecular site. For both of these disordered molecular sites, the atomic coordinates (for both molecular orientations) were refined with the application of geometric restraints, and isotropic atomic displacement parameters were refined. For the ordered molecular site, the atomic coordinates and anisotropic atomic displacement parameters were refined. In all cases, hydrogen atoms were positioned according to standard geometries.

Crystals of $C_8H_4Br_2$ (**8**) were grown by slow evaporation of solvent from a solution of **8** in a methanol–water mixture. The crystal was placed in a capillary tube to minimise the extent of sublimation, and single crystal X-ray diffraction data were recorded at ambient temperature. Information relating to the data collection, unit cell determination and space group assignment are summarised in Table 1. From the direct methods structure solution calculation and subsequent difference Fourier analysis, most non-hydrogen atoms were located, from which it was clear that there is orientational disorder of the $C_8H_4Br_2$ molecules. Specifically, the $C_8H_4Br_2$ molecules adopt three orientations, representing disorder of the bromine and ethynyl substituents among three sites corresponding to the 1, 3 and 5 positions on the benzene ring. The positions of the carbon atoms of the benzene ring in the three molecular orientations are indistinguishable. In structure refinement calculations, the three molecular orientations were allowed to have different occupancies, which refined to 65, 25 and 10% in the final refinement calculations. For the major molecular orientation (65% occupancy), atomic coordinates and anisotropic atomic displacement parameters (isotropic for the ethynyl group) were refined. For the other molecular orientations (25 and 10% occupancies), atomic coordinates were refined with the application of geometric restraints, and isotropic atomic displacement parameters were refined. All hydrogen atoms were positioned according to standard geometries.

Crystals of $C_{10}H_5Br$ (**9**) were grown by slow evaporation of solvent from a solution of **9** in a methanol–water mixture. As the crystals are susceptible to sublimation, the crystal was placed in a capillary tube and single crystal X-ray diffraction data were recorded below ambient temperature (263 K). Information relating to the data collection, unit cell determination and space group assignment are summarised in Table 1. From the direct methods structure solution calculation and subsequent difference Fourier analysis, most non-hydrogen atoms were located, from which it was clear that there is orientational disorder of the $C_{10}H_5Br$ molecules. Specifically, the $C_{10}H_5Br$ molecules adopt three orientations, corresponding to disorder of the bromine and ethynyl substituents among the three sites corresponding to the 1, 3 and 5 positions on the benzene ring. The positions of the carbon atoms of the benzene ring in the three molecular orientations are indistinguishable. In structure refinement calculations, the three molecular orientations were allowed to have different occupancies, which refined to 86, 7 and 7% in the final refinement calculations. For the major molecular orientation (86% occupancy), atomic coordinates and anisotropic atomic displacement parameters were refined. For the other molecular orientations (7% occupancies), atomic coordinates were refined with the application of geometric restraints, and isotropic atomic displacement parameters were refined. All hydrogen atoms were positioned according to standard geometries.

Crystals of $C_{10}H_5F$ (**11**) were grown by slow evaporation of solvent from a solution of **11** in a methanol–water mixture. As the crystals are susceptible to sublimation, the crystal was placed in a capillary tube and single crystal X-ray diffraction data were recorded below ambient temperature (243 K). Information relating to the data collection, unit cell determination and space group assignment are summarised in Table 1. From the direct methods structure solution calculation and subsequent difference Fourier analysis, most non-hydrogen atoms were located, from which it was clear that there is orientational disorder of the $C_{10}H_5F$ molecules. However, unlike the situation for **8** and **9**, the $C_{10}H_5F$ molecules in the crystal structure of **11** adopt only two orientations, corresponding to disorder of the fluorine and one ethynyl substituent between two sites. The position of the other ethynyl group is ordered, and the positions of the carbon atoms of the benzene ring in the two molecular orientations are indistinguishable. In structure refinement calculations, the two molecular orientations were allowed to have different occupancies, which refined to 63 and 37% in the final refinement calculations. For the major molecular orientation (63% occupancy), atomic coordinates and anisotropic atomic displacement parameters were refined. For the minor molecular orientation (37% occupancy), atomic coordinates were refined with the application of geometric restraints, and isotropic atomic displacement parameters were refined. All hydrogen atoms were positioned according to standard geometries. An attempt was also made to refine a disorder model analogous to that found for **8** and **9**, with three orientations of the $C_{10}H_5F$ molecule corresponding to disorder of the fluorine and ethynyl substituents among three sites corresponding to the 1, 3 and 5 positions on the benzene ring. However, in these refinements, the occupancy of one of the molecular orientations tended to zero; this model therefore converged towards the disorder model with two molecular orientations discussed above.

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