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Additivity of Ring Distortions in Halogen-Substituted Aromatics: a Gas-Phase Electron Diffraction and Computational Study

Derek A. Wann, Sarah L. Masters,† Heather E. Robertson, and David W. H. Rankin*

School of Chemistry, University of Edinburgh, West Mains Road, Edinburgh, U.K. EH9 3JJ

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The gas-phase structures of 1,2,3-trifluorobenzene, 1,3,5-trifluorobenzene, 2,6-difluoropyridine, and 2,6-dichloropyridine have been determined using electron diffraction and computational methods. The accuracy afforded by modern experimental methods has allowed subtle trends to be identified in the geometrical parameters of the rings. Comparisons have also been made between experimental and theoretical structures. Although the effects of multiple fluorine substituents on a benzene ring are shown to be more or less additive, distortions caused by replacement of a ring carbon atom by nitrogen and by halogen substituents are not.

Introduction

Replacing a hydrogen atom in a molecule by another atom or functional group can have a dramatic effect on the chemical and physical properties of a substance. Caused primarily by the modification of the electronic distribution within the molecule, the effects on reactivity and on some spectroscopically observed properties can be sizable. The geometry of the molecule is also affected, though the effects are usually less pronounced, and accurate experimental techniques are required to observe these changes. Ideally, distortions should be probed in the gas phase, where intermolecular interactions are minimized. As gas-phase electron diffraction (GED) is one of very few methods for obtaining accurate gas-phase structures for molecules larger than a few atoms, it is the technique of choice for studying these distortions.

Benzene derivatives are especially useful for studying changes in molecular geometry upon replacing a hydrogen atom by a more electronegative element. Aromatic rings are relatively rigid and often have a high degree of symmetry, which also helps when determining GED structures by reducing the number of refineable parameters. Simple halogenated ring systems are readily available and well suited for investigating the differences in the C−C bond lengths and C−C−C ring angles.

As gas-phase structures play a major role in the definition of force-field parameters in molecular mechanics programs, it is important to have accurate structures for key molecules, and to demonstrate that empirical relationships between structures are valid. With applications of molecular mechanics to drug design, in which fluorine substituents are increasingly significant, the structural consequences of fluorine atoms on aromatic structures are particularly important.

Ring distortions in a benzene derivative were first revealed in 1956 during a GED study of phenylsilane.[1] The best fit was obtained when the internal ring angles at the ipso and para positions were fixed at 117.4° and 120.8°, respectively. X-ray crystallography was subsequently used to provide further evidence of these C−C−C angles.[2] Extensive systematic studies of ring distorsions have since been performed using GED and quantum chemical methods by Hargittai and Domenicano,[3] and the data have been rationalized, mainly in terms of the electronegativities of the substituents. Their work was based primarily on benzene derivatives with just one substituent. In principle, more accurate measures of distortion can be obtained by studies of multiply substituted systems, particularly the most symmetrical 1,4-disubstituted and 1,3,5-trisubstituted compounds. However, it is first necessary to investigate the relative effects of single and multiple substitutions. As part of our investigations of the effects of halogen substitution on ring systems, we have therefore studied the molecules 1,2,3-trifluorobenzene, **1**, 1,3,5-trifluorobenzene, **2**, 2,6-difluoropyridine, **3**, and 2,6-dichloropyridine, **4**, using GED and high-level ab initio molecular orbital calculations. The structure of **2** has previously been determined using X-ray diffraction[4] and several times using GED,[5−7] and the publication of various different gas-phase structures suggests that there have been problems determining the molecular structure. The most recent GED study of **2** was published in 1992, and in the years since then, the use of computational techniques to aid structure determination has advanced. The SARACEN method[8] is now used routinely to allow flexible restraints to be applied during the GED refinement process, giving a more complete structure, although in the case of **2** it may not lead to great improvements because of the small number of parameters required to describe its geometry. The accurate calculation of molecular force fields also allows for the use of the SHRINK program[9] to determine curvilinear corrections, thus accounting accurately for the shrinkage effects[10] experienced in GED experiments.

We have chosen to study **1** and **2** because they are the two most symmetrical trifluorobenzenes. In contrast to the difluorobenzenes, where all three possess at least one mirror plane perpendicular to the plane of the ring, 1,2,4-trifluorobenzene has only C_s symmetry. The choice of **3** and **4** reflects the fact that they can also be considered as substituted benzene rings, with a nitrogen atom replacing a CH fragment and two halogen atoms replacing hydrogen atoms in the ortho positions. Much less effort has been made to study ring distortion effects in pyridines. The inclusion of N changes the ring geometry very substantially,[11] but we have investigated whether the subsequent addition of halogen atoms distorts the ring in an additive manner or otherwise. In **4** the fluorine atoms have been replaced by the

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* Corresponding author. E-mail: d.w.h.rankin@ed.ac.uk.

† Formerly Sarah L. Hinchley.

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TABLE 1: Refined (r_{h1}) and Calculated (r_e) Geometric Parameters for 1,2,3-Trifluorobenzene, 1, from the GED Study with Restraints Applied Using SARACEN[a,b]

parameter		r_{h1}	r_e	restraint
	Independent			
p_1	rC−C average	139.7(2)	139.5	
p_2	rC−C difference 1	0.8(2)	0.8	0.8(2)
p_3	rC−C difference 2	0.4(2)	0.4	0.4(2)
p_4	rC−F average	132.8(3)	133.8	
p_5	rC−F difference	0.8(3)	0.8	0.8(3)
p_6	rC−H mean	108.1(6)	108.5	108.5(10)
p_7	∠C(1)−C(2)−C(3)	119.5(8)	118.8	
p_8	∠C(2)−C(1)−F(1)	118.4(3)	118.3	
p_9	∠C(4)−C(5)−C(6)	119.3(12)	120.8	
p_{10}	∠C(5)−C(4)−H(4)	122.0(2)	122.1	122.1(2)
	Dependent			
p_{11}	rC(5)−C(6)	140.2(2)	139.9	
p_{12}	rC(2)−C(3)	139.6(2)	139.5	
p_{13}	rC(3)−C(4)	139.2(2)	139.1	
p_{14}	rC(2)−F(2)	132.4(3)	133.4	
p_{15}	rC(1)−F(1)	133.2(3)	134.1	
p_{16}	∠C(3)−C(4)−C(5)	119.5(6)	119.0	
p_{17}	∠C(2)−C(3)−C(4)	120.4(4)	121.3	
p_{18}	∠C(6)−C(1)−F(1)	121.2(2)	120.5	

[a] Refers to the MP2/6-311++G** calculation. [b] Distances (r) are in pm, angles (∠) in degrees. See text for parameter definitions and Figure 1a for atom numbering. The figures in parentheses are the estimated standard deviations of the last digits.

less electronegative chlorine atoms, which normally have much smaller effects than fluorine on the geometry of the ring.

Experimental Section

Synthesis. Samples of each compound **1**−**4** were purchased from Aldrich and were used without further purification.

Gas-Phase Electron Diffraction. Data were collected for **1**−**4** using the Edinburgh gas-phase electron diffraction apparatus.[12] An accelerating voltage of 40 kV was used, resulting in an electron wavelength of approximately 6.0 pm. The nozzle and sample temperatures, weighting points for the off-diagonal weight matrices, correlation parameters and scale factors for all molecules are given in Table S1. Also included are the electron wavelengths, determined from the scattering patterns for benzene, which were recorded immediately after the sample patterns. For **1**−**3**, the scattering intensities were measured at the Institute of Astronomy, Cambridge, using a PDS densitometer and converted to mean optical densities as a function of the scattering variable, *s*, using an established program.[13] In the case of the photographic films for **4**, the scanning was performed in-house using an Epson Expression 1680 Pro flatbed scanner as part of a method that is now used routinely in Edinburgh.[14] The data reduction and least-squares refinement processes were carried out using the ed@ed program,[15] employing the scattering factors of Ross et al.[16]

Computational Details. All calculations were performed on a Linux 12-processor Parallel Quantum Solutions (PQS) workstation[17] running the Gaussian 98 suite of programs.[18] The geometries of **1**−**4** were calculated initially using the Hartree−Fock level of theory and a 3-21G* basis set[19] (RHF/3-21G*), followed by the use of the 6-31G* basis set.[20] The Hartree−Fock method ignores electron correlation, a phenomenon that is likely to be important in the calculation of the geometries of molecules with electronegative halogen atoms and electron-rich benzene rings. Calculations to include electron correlation using the MP2 method[21] were performed with various Pople-style basis sets (6-31G*, 6-311G*, 6-311+G*, and 6-311++G**).[22] An analytical force field (RHF/6-31G*) was calculated for each molecule to provide estimates of the amplitudes of vibration (u_{h1}) and curvilinear corrections (k_{h1}), from the SHRINK program,[9] for use in the GED refinements.

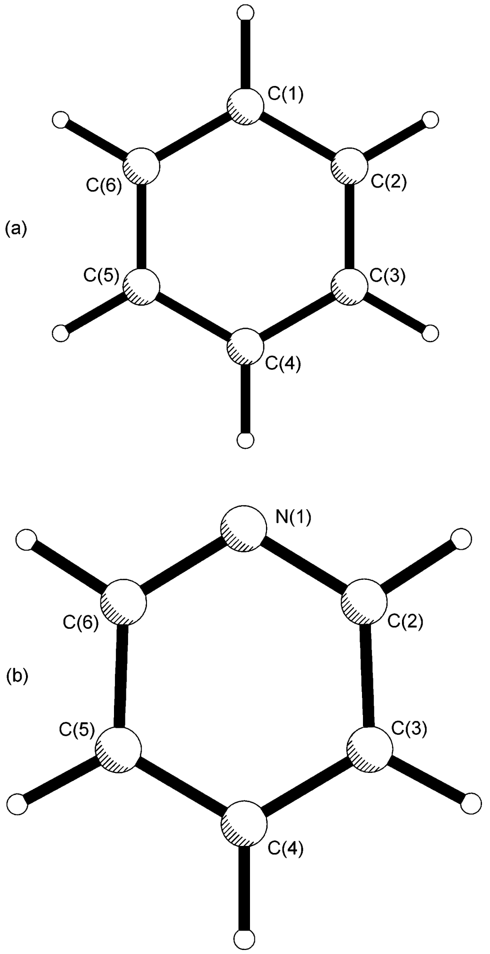

Figure 1. General structures of (a) benzene and (b) pyridine showing the standard numbering schemes employed throughout this work. In all cases substituents are assigned the same number as the carbon atoms to which they are bound.

Results

GED Study. On the basis of the calculations described above, models were written for **1**−**4**, allowing **1**, **3** and **4** each to have C_{2v} symmetry and **2** to have D_{3h} symmetry. The geometry of **1** was described using ten independent parameters, comprising six bond lengths and differences and four angles (Table 1). The bond lengths included the average C−C distance {[rC(H)−C(H) + rC(H)−C(F) + rC(F)−C(F)]/3} and two difference parameters, namely difference 1 (rC(H)−C(H) − {[rC(H)−C(F) + rC(F)−C(F)]/2}) and difference 2 [rC(H)−C(F) − rC(F)−C(F)] (p_{1-3}). The two individual C−F bond lengths were described as the average of and difference between the two distances (p_{4-5}). The difference was defined as C(1)−F(1) minus C(2)−F(2). Although C_{2v} symmetry allows for two different C−H distances, calculations (MP2/6-311++G**) suggested that the difference between the two was of the order of only 0.1 pm and, therefore, a single value was employed (p_6). The four angles were defined as ∠C(1)−C(2)−C(3), ∠C(2)−C(1)−F(1), ∠C(4)−C(5)−C(6), and ∠C(5)−C(4)−H(4) (p_{7-10}; see Figure 1a for atom numbering).

Molecules of 1,3,5-trifluorobenzene, **2**, have higher symmetry (D_{3h}) and can be described using only four parameters (Table 2). These are rC−C, rC−F, and rC−H (p_{1-3}) and the C−C(F)−C

TABLE 2: Refined (r_{h1}) and Calculated (r_e) Geometric Parameters for 1,3,5-Trifluorobenzene, 2, from the GED Study[a,b]

parameter		r_{h1}	r_e	restraint
Independent				
p_1	rC−F	133.4(2)	134.6	
p_2	rC−C	139.4(1)	139.2	
p_3	rC−H	108.4(9)	108.4	
p_4	∠C(2)−C(3)−C(4)	122.9(1)	123.2	
Dependent				
p_5	∠C(1)−C(2)−C(3)	117.1(1)	116.8	

[a] Refers to the MP2/6-311++G** calculation. [b] Distances (r) are in pm, angles (∠) in degrees. See text for parameter definitions and Figure 1a for atom numbering. The figures in parentheses are the estimated standard deviations of the last digits.

angle (p_4). The atom numbering for **2** is in accordance with that shown in Figure 1(a).

The model geometries for **3** and **4** were identical (except for substituting Cl for F) and described in a similar manner to that for **1**, using five bond lengths and differences and four angle parameters (Table 3). The average of the two C−C distances ({r[C(H)−C(H)] + r[C(H)−C(F/Cl)]}/2) and the difference [C(3)−C(4) minus C(2)−C(3)] between them (p_{1-2}) were used, as were parameters describing the C−F/Cl bond length and the C−N distance (p_{3-4}). Again, a single value was used to describe the C−H distances (p_5). The angles used in the model were ∠C(3)−C(4)−C(5), ∠C(4)−C(3)−H(3), ∠C(6)−N−C(2), and ∠N−C(2)−F/Cl(2) (p_{6-9}; see Figure 1b for atom numbering).

All independent geometric parameters for each molecule **1**−**4** were subject to least-squares refinement, with restraints applied where necessary, using the SARACEN method[8] (Tables 1−3). Each restraint was based on the convergence of the values of that parameter, as seen in the series of calculations that were performed. All data were weighted according to their uncertainties.[8] In addition, seven amplitudes of vibration (two of which were restrained) were refined for **1**, with nine refined for **2** (with one restraint). For **3** and **4**, seven and eight amplitudes were refined, respectively, with only those for the C−H-bonded distances needing to be restrained. (See Tables S2−S5 for lists of amplitudes of vibration for molecules **1**−**4**, respectively.)

The success of a refinement is shown by the R factor, which for **1** was $R_G = 0.040$ ($R_D = 0.030$), for **2** was $R_G = 0.055$ ($R_D = 0.039$), for **3** was $R_G = 0.048$ ($R_D = 0.029$), and for **4** was $R_G = 0.060$ ($R_D = 0.033$). The goodness of fit of the radial-distribution and experimental-minus-theoretical difference curves can be seen in Figure 2, and in the molecular-scattering intensity curves (Figures S1−S4). The least-squares correlation matrices are given in Tables S6−S9 and coordinates for the final GED structures are in Tables S10−S13.

Discussion

The structures of 1,2,3-trifluorobenzene, **1**, 1,3,5-trifluorobenzene, **2**, 2,6-difluoropyridine, **3**, and 2,6-dichloropyridine, **4**, have been determined by gas-phase electron diffraction and the results compared to structures obtained from ab initio calculations (MP2/6-311++G**). In general, the experimental and theoretical parameters agree very well. For **1**, the GED values for the three C−C distances match the calculated values within experimental error, as do ∠C(1)−C(2)−C(3), ∠C(3)−C(4)−C(5), and ∠C(2)−C(1)−F(1) (Table 1). The C(2)−C(1)−F(1) angle is less than 120° and the C(6)−C(1)−F(1) angle greater, suggesting that the repulsion of F(1) and F(3) by F(2) manifests itself in a lengthening of C−F(1/3) by about 1 pm with respect to C−F(2), rather than in a widening of angles.

Although the gas-phase structure of **2** has been determined several times in the past,[5−7] this is the first study to use SHRINK to incorporate curvilinear corrections[9] and to make use of the SARACEN method.[8] Parameters from this and two previous refinements of **2** are given in Table 4, where it should be noted that distances have been quoted as r_g values to aid comparison. Further discussion of the similarities and differences between the various structures is given in Supporting Information.

Assuming that the length of the C−C bond in benzene is $r_a = 139.75(3)$ pm, we find that $r_g = 139.97(3)$ and $r_{h1} = 139.91(3)$ pm. Tables 1 and 2 contain the values for rC−C and ∠C−C−C from GED and theoretical studies of **1** and **2**. It can be seen by comparison with the GED values for benzene that the substitution of fluorine atoms for hydrogen causes a distortion of the C−C−C angles with some angles becoming wider than 120° and others narrower. Lengthening and shortening of rC−C is also observed. For monosubstituted fluorobenzene, these effects can easily be recognized and ascribed to the inclusion of the single fluorine atom in the ring. Where the ring is multisubstituted it has been reported that these effects are, to a reasonable approximation, additive.[3] Following the method used in ref 3, the additive nature of these effects can be demonstrated using the distortions of monofluorobenzene to give a good approximation of the distortions in **1** and **2**. The distortions associated with having a single fluorine substituent on a benzene ring are $\Delta\alpha_F = 3.4°$, $\Delta\beta_F = -2.0°$, $\Delta\gamma_F = 0.3°$ and $\Delta\delta_F = 0.0°$, where α is the internal ring angle at the site of the substitution and β, γ and δ are ortho, meta, and para to the substituent, respectively.[3] Table 5 shows the empirically predicted, theoretical and experimental values for some of the internal angles in **1** and **2**. In general, the degree of correlation between the predicted values and the GED values is good, with agreement on the direction of the distortion (greater or less than 120°) in all but one case. It is, however, noticeable in that case that that GED value has a large standard deviation and the MP2-calculated value is close to the predicted one.

In addition to the two trifluorobenzenes, **1** and **2**, studied here there is a third geometrical isomer, 1,2,4-trifluorobenzene, which is less symmetrical (C_s) than the other two and is, therefore, less well suited to investigation by GED. Whereas the geometry of 1,3,5-trifluorobenzene can be fully described using four parameters, the 1,2,4-isomer requires 21 independent parameters. The bond lengths and angles obtained for this molecule from ab initio calculations performed at the MP2/6-311++G** level of theory are shown in Table 6. (See Figure 1a for atom numbering.) The internal ring angles are, as expected, wider than 120° where the substituent is F and are narrower than 120° for a hydrogen substituent. It is notable that for the two adjacent F substituents, the ring angles (120.8° and 120.2°) are considerably smaller than the angle at the four-position (122.5°). This can be attributed to the narrowing effect at the β angle of the adjacent fluorine substituent. A similar phenomenon is observed in the structure of **1**, where angles C(2)−C(3)−C(4) and C(6)−C(1)−C(2) are calculated to be 121.3° and C(1)−C(2)−C(3) is 118.8°. In 1,2,4-trifluorobenzene, the internal angle at C(3) is smaller than either of the other two angles at carbons bonded to hydrogen, caused by the additive effects of being ortho to two fluorine atoms. Table 6 gives empirically predicted values for each of the internal C−C−C angles, based on the prediction factors taken from ref 3. Although the predicted values are correct in terms of the widening or narrowing of the angles, many are overestimated or underestimated by 1° or more. Lengthening and shortening of the C−C bonds relative to benzene is observed for 1,2,4-trifluorobenzene. Values less than

TABLE 3: Refined (r_{h1}) and Calculated (r_e) Geometric Parameters for 2,6-Difluoropyridine, 3, and 2,6-Dichloropyridine, 4, from the GED Study with Restraints Applied Using SARACEN[a,b]

parameter		3			4		
		r_{h1}	r_e	restraint	r_{h1}	r_e	restraint
		Independent					
p_1	rC−C average	139.6(2)	139.5		138.6(2)	139.7	
p_2	rC−C difference	0.5(2)	0.5	0.5(2)	0.2(2)	0.2	0.2(1)
p_3	rC−F/Cl	133.7(3)	133.9		171.8(3)	173.3	
p_4	rC−N	132.0(4)	132.1		132.7(3)	133.2	
p_5	rC−H mean	108.4(4)	108.5	108.5(4)	108.3(2)	108.5	108.5(2)
p_6	∠C(3)−C(4)−C(5)	120.0(4)	119.7		120.1(3)	119.5	
p_7	∠C(4)−C(3)−H(3)	123.0(5)	122.9	122.9(3)	123.2(5)	122.9	122.9(5)
p_8	∠C(6)−N−C(2)	115.5(5)	115.8		116.4(3)	116.8	
p_9	∠N−C(2)−F/Cl(2)	115.5(3)	115.6	115.6(3)	115.9(2)	115.6	115.6(3)
		Dependent					
p_{10}	rC(3)−C(4)	139.8(2)	139.7		138.7(2)	139.8	
p_{11}	rC(2)−C(3)	139.3(2)	139.2		138.5(2)	139.6	
p_{12}	∠C(2)−C(3)−C(4)	116.1(3)	116.5		116.9(2)	117.3	
p_{13}	∠N−C(2)−C(3)	126.1(3)	125.8		124.9(2)	124.6	

[a] Refers to the MP2/6-311++G** calculation. [b] Distances (r) are in pm, angles (∠) in degrees. See text for parameter definitions and Figure 1b for atom numbering. The figures in parentheses are the estimated standard deviations of the last digits.

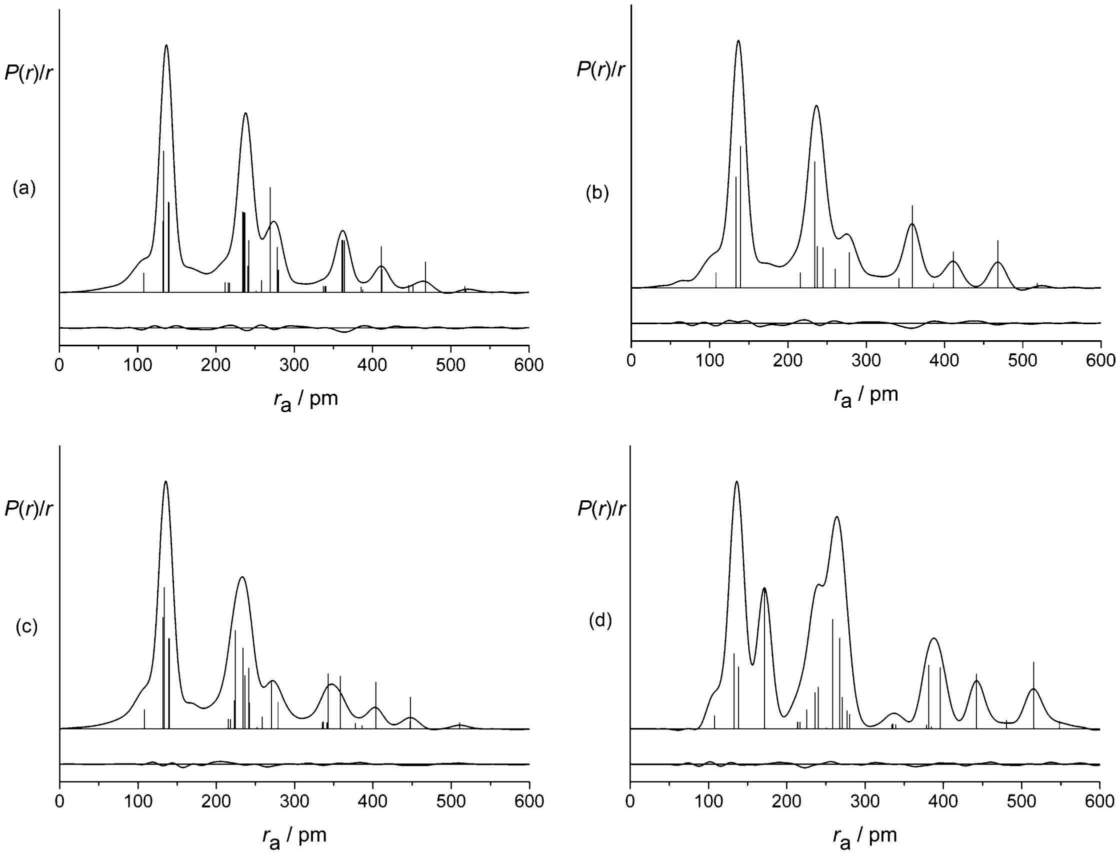

Figure 2. Experimental radial-distribution curves and theoretical-minus-experimental difference curves for the refinements of (a) 1,2,3-trifluorobenzene, **1**, (b) 1,3,5-trifluorobenzene, **2**, (c) 2,6-difluoropyridine, **3**, and (d) 2,6-dichloropyridine, **4**. Before Fourier inversion the data were multiplied by $s\exp(-0.00002s^2)/(Z_X - f_X)(Z_Y - f_Y)$, where for **1**−**3** X = C and Y = F, and for **4** X = C and Y = Cl.

the GED value for benzene are seen for each of the bonds to a carbon bound to fluorine. The only rC−C longer than that in benzene is found where both carbon atoms have an H substituent.

The GED structures of 1,2,3-trichlorobenzene[23] and 1,3,5-trichlorobenzene[24] have previously been published, and comparison of these structures with their fluoro analogues is given in Supporting Information. GED studies have also previously been performed for other fluorinated benzenes, with trends similar to those in this paper reported. A comparison, including references to monofluorobenzene,[25,26] 1,2,4,5-tetrafluorobenzene,[27] and hexafluorobenzene,[28] is given in Supporting Information.

Compared to the amount of structural work that has been performed on substituted benzenes, relatively little is known about trends in substituted pyridines. The values for rC−N, rC−C, ∠C−N−C, ∠C−C−N, and ∠C−C−C obtained from the GED studies of **3** and **4** are included in Table 3, where they are compared to the values given by calculations (MP2/6-311++G**), and in Table 7, they are compared to experimental gas-phase values obtained for pyridine.[11] Here, as was the case for **2**, r_g values have been calculated for the bond lengths in **3**

TABLE 4: Comparison of the Molecular Geometry of 1,3,5-Trifluorobenzene, 2, Determined from Three Separate GED Studies and ab Initio Calculations (MP2/6-311++G)[a]**

	previous studies							
	ref 6		ref 7		this study			MP2
parameter	r_a	r_g	r_a	r_g	r_a	r_g	r_{h1}	r_e
*r*C−C	138.8(1)	138.9(1)	138.71(7)	138.9(3)	139.4	139.4	139.4(4)	139.2
*r*C−F	134.0(2)	133.9(2)	134.4(1)	134.6(3)	133.2	133.3	133.5(2)	134.6
*r*C−H	106.7(7)	106.9(7)	109.0(4)	109.6(6)	107.0	107.1	108.3(10)[b]	108.4
∠C−C(F)−C	124.0(1)	123.7(1)	*c*	123.9(1)			122.9(6)	123.2
∠C−C(H)−C	*c*	*c*	*c*	*c*			117.1(6)	116.8

[a] Distances (*r*) are in pm and angles (∠) are in degrees. [b] *r*C−H was determined using the SARACEN method. (See text for full description of refinement process.) [c] Values were not quoted.

TABLE 5: Predicted, Theoretical, and Experimental Values for the C−C−C Angles in 1 and 2[a]

	1			2		
	predicted	MP2	GED	predicted	MP2	GED
∠C(1)−C(2)−C(3)	119.4	118.8	119.5(8)	116.0	116.8	117.1(1)
∠C(2)−C(3)−C(4)	121.7	121.3	120.4(4)	124.0	123.2	122.9(1)
∠C(3)−C(4)−C(5)	118.3	119.0	119.5(6)			
∠C(4)−C(5)−C(6)	120.6	120.8	119.3(12)			

[a] Angles (∠) in degrees. Empirical predictions made on the basis of constants obtained from reference 3. The 6-311++G** basis set was used for all calculations.

TABLE 6: Calculated (r_e) Geometric Parameters for 1,2,4-Trifluorobenzene[a]

parameter	MP2/6-311++G**
*r*C(1)−C(2)	139.6
*r*C(2)−C(3)	139.1
*r*C(3)−C(4)	139.3
*r*C(4)−C(5)	139.1
*r*C(5)−C(6)	140.0
*r*C(6)−C(1)	139.0
*r*C(1)−F(1)	134.2
*r*C(2)−F(2)	134.0
*r*C(4)−F(4)	134.8
∠C(1)−C(2)−C(3)	120.8 (121.7)
∠C(2)−C(3)−C(4)	117.9 (116.3)
∠C(3)−C(4)−C(5)	122.5 (123.7)
∠C(4)−C(5)−C(6)	118.2 (118.3)
∠C(5)−C(6)−C(1)	119.9 (118.6)
∠C(6)−C(1)−C(2)	120.2 (121.4)
∠C(6)−C(1)−F(1)	120.5
∠C(2)−C(1)−F(1)	119.3
∠C(1)−C(2)−F(2)	119.3
∠C(3)−C(2)−F(2)	119.8
∠C(3)−C(4)−F(4)	118.3
∠C(5)−C(4)−F(4)	119.2

[a] The values in parentheses are those predicted empirically for the internal C−C−C angles. Distances (*r*) are in pm, angles (∠) in degrees. See text for parameter definitions and Figure 1a for atom numbering. Empirical predictions made on the basis of constants were obtained from ref 3.

TABLE 7: Comparison of GED Values (Including r_g Values for Distances for Comparison) for Pyridine, 2,6-Difluoropyridine, 3, and 2,6-Dichloropyridine, 4[a]

	pyridine[b]	3		4	
parameter	r_g	r_g	r_{h1}	r_g	r_{h1}
*r*N−C(2)	134.4(6)	131.9	132.0(4)	133.0	132.7(3)
*r*C(2)−C(3)	139.8(6)	139.3	139.8(2)	138.8	138.7(2)
*r*C(3)−C(4)	139.9(6)	140.0	139.3(2)	138.7	138.5(2)
∠C(6)−N−C(2)	116.1(4)		115.5(5)		116.4(3)
∠N−C(2)−C(3)	124.6(4)		126.1(3)		124.9(1)
∠C(2)−C(3)−C(4)	117.8(4)		116.1(3)		116.9(2)
∠C(3)−C(4)−C(5)	119.1(4)		120.0(4)		120.1(3)

[a] Distances (*r*) are in pm, angles (∠) in degrees. See text for parameter definitions and Figure 1b for atom numbering. [b] Values taken from ref 11, in which the estimated standard deviations were estimated to be 0.6 pm for a heavy-atom bond length and 0.4° for angles.

TABLE 8: Predicted, Theoretical, and Experimental Values for the Internal Ring Angles in 3 and 4[a]

	3			4		
	predicted	MP2	GED	predicted	MP2	GED
∠C(6)−N−C(2)	112.7	115.8	115.5(5)	115.1	116.8	116.4(3)
∠N−C(2)−C(3)	127.6	125.8	126.1(3)	125.5	124.6	124.9(1)
∠C(2)−C(3)−C(4)	116.6	116.5	116.1(3)	117.5	117.3	116.9(2)
∠C(3)−C(4)−C(5)	118.9	119.7	120.0(4)	119.3	119.5	120.1(3)

[a] Angles (∠) in degrees. See text for the origin of the empirical predictions. The 6-311++G** basis set was used for all calculations.

and **4** to allow direct comparison with the r_g values quoted for pyridine. For **3** both the GED-determined C−C and C−N distances and the C−C−C, N−C−C, and C−N−C angles are in excellent agreement with theory (Table 3). For **4** the C−C and C−N distances are overestimated by theory by up to 1 pm, although the angles are still in good agreement.

As expected, the inclusion of N in place of a CH fragment in benzene has the effect of greatly decreasing the ipso angle, coupled to shortening of the 1−2 bond. There is, however, no noticeable effect on the other ring bond lengths, with C(2)−C(3) and C(3)−C(4) both lying within 0.2 pm of the value found in benzene. The effect on the internal ring angles is more pronounced with significant deviations from 120° required to compensate for the inclusion of N in the ring: ∠N−C(2)−C(3) is 124.6(4)°, ∠C(2)−C(3)−C(4) is 117.8(4)°, and ∠C(3)−C(4)−C(5) is 119.1(4)°.

It is noticeable that substituting F for H at the 2 and 5 positions in pyridine causes the internal ring angle at N to narrow and those at the fluorine-substituted carbons to widen. The additive nature of the ring distortions caused by N and by fluorine and chlorine substituents has been investigated using the data in Table 8. The predictions are based on those parameters listed above for F and the following parameters for N: $\Delta\alpha_N = -3.3°$, $\Delta\beta_N = +3.9°$, $\Delta\gamma_N = -1.4°$, and $\Delta\delta_N = -1.7°$, and for Cl: $\Delta\alpha_{Cl} = +1.1°$, $\Delta\beta_{Cl} = -0.8°$, $\Delta\gamma_{Cl} = +0.5°$ and $\Delta\delta_{Cl} = -0.3°$. The parameters for N and Cl are simply derived from the effects with respect to benzene, calculated at the MP2/6-311++G** level, for pyridine and chlorobenzene, respectively.

Table 8 shows that in this case the additive model is poor. Changes in ring angles at the substitution sites and at nitrogen are much smaller than predicted, although fluorine clearly has a greater effect than chlorine.

Conclusion

Empirically derived factors have been used to predict the structures of 1,2,3-trifluorobenzene, 1,3,5-trifluorobenzene, 2,6-

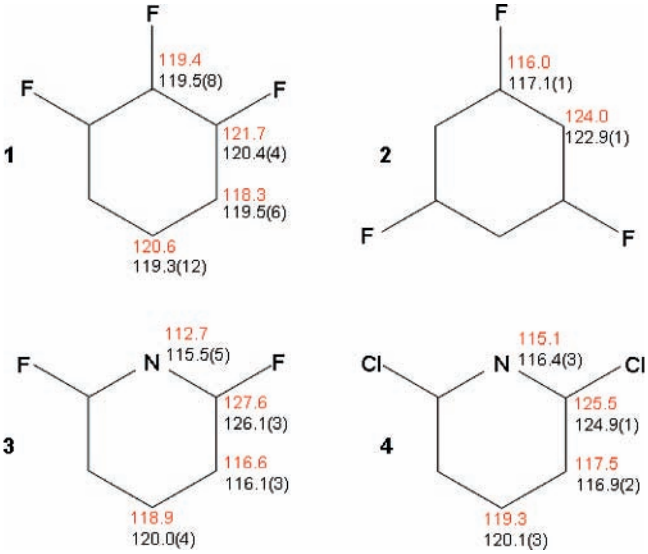

Figure 3. Pictures of molecules **1**−**4** illustrating the deviations of the bond angles from 120°. Numbers in red are predicted empirically and those in black are GED values. All angles are in degrees.

difluoropyridine, and 2,6-dichloropyridine. Figure 3 gives a pictorial representation of our findings. For the trisubstituted benzenes the predictions of whether an angle will be wider or narrower than 120° is generally accurate and the absolute values are usually within about 1° of the GED-determined values. By taking this empirical method a step further and substituting N into the six-membered ring, we showed that the extent to which the effects of substitution are additive is lessened. Where the pyridine is 2,6-substituted by fluorine, the predicted angles are further from the experimental ones than when chlorine is the substituent.

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Supporting Information Available: Detailed information is available on the electron diffraction experiments, interatomic distances, amplitudes of vibration and correlation matrices from the least-squares refinements, calculated geometric coordinates and energies, and molecular-scattering intensity curves. There are also sections detailing how the results of this refinement of **2** compare to those given by two previous refinements, comparisons of the structures of trifluorobenzenes with those of trichlorobenzenes, and a section highlighting similarities and differences between the structures of **1** and **2** and those of other fluorobenzenes. This material is available free of charge via the Internet at http://pubs.acs.org.

References and Notes

(1) Keidel, F. A.; Bauer, S. H. *J. Chem. Phys.* **1956**, *25*, 1218.

(2) Domenicano, A.; Vaciago, A.; Coulson, C. A. *Acta Crystallogr., Sect. B: Struct. Crystallogr. Cryst. Chem.* **1975**, *31*, 1630.

(3) Domenicano, A. Substituted Benzene Derivatives. In *Structural Information for Selected Classes of Compounds*; Hargittai I., Hargittai, M., Eds.; Stereochemical Applications of Gas-Phase Electron Diffraction, Part B; VCH Publishers: Weinheim, Germany, 1998 (see also references therein).

(4) Thalladi, V. K.; Weiss, H.-C.; Bläser, D.; Boese, R.; Nangia, A.; Desiraju, G. R. *J. Am. Chem. Soc.* **1998**, *120*, 8702.

(5) Katada, K.; Kimura, K. In *Structural Chemistry and Molecular Biology*; Rich A., Davidson, N., Eds.; Freeman: San Francisco, 1968; p 653.

(6) Almenningen, A.; Hargittai, I.; Brunvoll, J.; Domenicano, A.; Samdal, S. *J. Mol. Struct.* **1984**, *116*, 199.

(7) Ramondo, F.; Portalone, G.; Domenicano, A.; Schultz, G.; Hargittai, I. *J. Mol. Struct.* **1992**, *269*, 367.

(8) Blake, A. J.; Brain, P. T.; McNab, H.; Miller, J.; Morrison, C. A.; Parsons, S.; Rankin, D. W. H.; Robertson, H. E.; Smart, B. A. *J. Phys. Chem.* **1996**, *100*, 12280. Brain, P. T.; Morrison, C. A.; Parsons, S.; Rankin, D. W. H. *J. Chem. Soc., Dalton Trans.* **1996**, 4589. Mitzel, N. W.; Rankin, D. W. H. *Dalton Trans.* **2003**, 3650.

(9) Sipachev, V. A. *J. Mol. Struct.* (*THEOCHEM*) **1985**, *121*, 143. Sipachev, V. A. *J. Mol. Struct.* **2001**, *576*, 67.

(10) Bastiansen, O.; Trætteberg, M. *Acta Crystallogr.* **1960**, *13*, 1108. Morino, Y.; Cyvin, S. J.; Kuchitsu, K.; Iijima, T. *J. Chem. Phys.* **1962**, *36*, 1109. Stølevik, R.; Seip, H. M.; Cyvin, S. J. *Chem. Phys. Lett.* **1972**, *15*, 263.

(11) Pyckhout, W.; Horemans, N.; Alsenoy, C. V.; Geise, H. J.; Rankin, D. W. H. *J. Mol. Struct.* **1987**, *156*, 315.

(12) Huntley, C. M.; Laurenson, G. S.; Rankin, D. W. H. *J. Chem. Soc., Dalton Trans.* **1980**, 954.

(13) Lewis, J. R.; Brain, P. T.; Rankin, D. W. H. *Spectrum* **1997**, *15*, 7.

(14) Fleischer, H.; Wann, D. A.; Hinchley, S. L.; Borisenko, K. B.; Lewis, J. R.; Mawhorter, R. J.; Robertson, H. E.; Rankin, D. W. H. *Dalton Trans.* **2005**, 3221.

(15) Hinchley, S. L.; Robertson, H. E.; Borisenko, K. B.; Turner, A. R.; Johnston, B. F.; Rankin, D. W. H.; Ahmadian, M.; Jones, J. N.; Cowley, A. H. *Dalton Trans.* **2004**, 2469.

(16) Ross, A. W.; Fink, M.; Hilderbrandt, R. In *International Tables for Crystallography*; Wilson, A. J. C., Ed.; Kluwer Academic Publishers: Dordrecht, Netherlands, 1992; Vol. C, p 245.

(17) Parallel Quantum Solutions, Fayetteville, AR.

(18) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Zakrzewski, V. G.; Montgomery, J. A., Jr.; Stratmann, R. E.; Burant, J. C.; Dapprich, S.; Millam, J. M.; Daniels, A. D.; Kudin, K. N.; Strain, M. C.; Farkas, O.; Tomasi, J.; Barone, V.; Cossi, M.; Cammi, R.; Mennucci, B.; Pomelli, C.; Adamo, C.; Clifford, S.; Ochterski, J.; Petersson, G. A.; Ayala, P. Y.; Cui, Q.; Morokuma, K.; Malick, D. K.; Rabuck, A. D.; Raghavachari, K.; Foresman, J. B.; Cioslowski, J.; Ortiz, J. V.; Baboul, A. G.; Stefanov, B. B.; Liu, G.; Liashenko, A.; Piskorz, P.; Komaromi, I.; Gomperts, R.; Martin, R. L.; Fox, D. J.; Keith, T.; Al-Laham, M. A.; Peng, C. Y.; Nanayakkara, A.; Gonzalez, C.; Challacombe, M.; Gill, P. M. W.; Johnson, B.; Chen, W.; Wong, M. W.; Andres, J. L.; Gonzalez, C.; Head-Gordon, M.; Replogle, E. S.; Pople, J. A. *Gaussian 98*, Revision A.7; Gaussian, Inc.: Pittsburgh, PA, 1998.

(19) Binkley, J. S.; Pople, J. A.; Hehre, W. J. *J. Am. Chem. Soc.* **1980**, *102*, 939. Gordon, M. S.; Binkley, J. S.; Pople, J. A.; Pietro, W. J.; Hehre, W. J. *J. Am. Chem. Soc.* **1982**, *104*, 2797. Pietro, W. J.; Francl, M. M.; Hehre, W. J.; DeFrees, D. J.; Pople, J. A.; Binkley, J. S. *J. Am. Chem. Soc.* **1982**, *104*, 5039.

(20) Hehre, W. J.; Ditchfield, R.; Pople, J. A. *J. Chem. Phys.* **1972**, *56*, 2257. Hariharan, P. C.; Pople, J. A. *Theor. Chim. Acta* **1973**, *28*, 213. Gordon, M. S. *Chem. Phys. Lett.* **1980**, *76*, 163.

(21) Møller, C.; Plesset, M. S. *Phys. Rev.* **1934**, *46*, 618.

(22) Krishnan, R.; Binkley, J. S.; Seeger, R.; Pople, J. A. *J. Chem. Phys.* **1980**, *72*, 650. McLean, A. D.; Chandler, G. S. *J. Chem. Phys.* **1980**, *72*, 5639.

(23) Blake, A. J.; Blom, R.; Cradock, S.; Davidson, S. L.; Rankin, D. W. H. *J. Mol. Struct.* **1990**, *240*, 95.

(24) Blom, R.; Cradock, S.; Davidson, S. L.; Rankin, D. W. H. *J. Mol. Struct.* **1991**, *245*, 369.

(25) Portalone, G.; Schultz, G.; Domenicano, A.; Hargittai, I. *J. Mol. Struct.* **1984**, *118*, 53.

(26) Pulay, P. *Mol. Phys.* **1969**, *17*, 197.

(27) Schei, S. H.; Almenningen, A.; Almlöf, J. *J. Mol. Struct.* **1984**, *112*, 301.

(28) Almenningen, A.; Bastiansen, O.; Seip, R.; Seip, H. M. *Acta Chem. Scand.* **1964**, *18*, 2115.