Gaseous and crystalline phase molecular structures of 4,6-dichloropyrimidine, 2,6-dichloropyrazine and 3,6-dichloropyridazine

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The gas-phase molecular structures of 4,6-dichloropyrimidine, 2,6-dichloropyrazine and 3,6-dichloropyridazine have been determined by electron diffraction (GED) and *ab initio* calculations, and are compared to their respective parent compounds to demonstrate the effects of chlorination on ring geometry. The crystal structures of the three dichloro compounds are also reported; the intermolecular contacts leading to distortions in the solid phases have been identified.

Introduction

Pyrimidine, pyrazine and pyridazine and their derivatives are key compounds in organic chemistry. Examples of each class of compound have been found in nature, most notably pyrimidine as a component of the four bases in DNA, while pyrazines are responsible for flavour in foodstuffs as diverse as cooked meats, cheese, tea and coffee. Many derivatives which possess biological activity have been synthesised, with applications including antibiotics and antihypertensive agents.

Reliable structural data for these rings are essential for use in molecular modelling programs. However, in many important compounds there are oxygen or nitrogen substituents, which distort the ring structure, but simple compounds with these substituents do not yield useful structural data for modelling, because proton shifts give isomeric forms. Chloro derivatives are therefore particularly important, because the electronegativity of chlorine is as close to those of nitrogen and oxygen as can be obtained with a simple substituent, and electronegativity is the major influence on ring distortion.

In this paper we present gas-phase structures for dichloro derivatives of pyrimidine, pyrazine and pyridazine, and these are compared with those previously reported for the parent compounds,[1,2] thus showing the effects of the electron-withdrawing substituents. Structures derived from gas-phase electron diffraction (GED) and rotational spectroscopy experiments are presented. In addition, *ab initio* calculations can be performed to high levels for these small, symmetrical molecules. We have therefore also been able to make use of the recently developed SARACEN (Structure Analysis Restrained by *Ab initio* Calculation for Electron diffractioN) method,[3] combining experimental and theoretical data to give a single structure, which makes optimum use of all available information.

Finally, we report crystal structures for all three compounds, and are able to identify the distortions which occur on crystallisation, and to investigate their origins.

Experimental

Ab initio calculations

All calculations were performed on a DEC Alpha APX 1000 workstation using the GAUSSIAN92 and 94 programs.[4–5]

Geometry optimisations. A graded series of geometry optimisation calculations was carried out for each molecule, from which the effects of increasing the quality of basis set and level of theory could be gauged. In the case of 4,6-dichloropyrimidine calculations were performed using standard gradient techniques at the SCF level of theory using the 3-21G,[6–8] 6-31G*[9–11] and 6-311G**[12–13] basis sets. The two larger basis sets were subsequently used for optimisations at the MP2(FC) level of theory, and an additional calculation was undertaken at the 6-31+G*/MP2 level to assess the effects of diffuse functions for heavy atoms on molecular parameters. This effect was found to be negligible and so neither this nor the 6-311G**/SCF calculation was performed for the remaining structures.

Frequency calculations. These were performed at the 3-21G*/SCF and 6-31G*/SCF levels for each molecule, confirming C_{2v} symmetry as a local minimum in each case. The force constants obtained in the higher calculations were subsequently used in the construction of forcefields for the dichloro compounds using the ASYM40 program.[14] Since no fully assigned vibrational spectra were available for these compounds, the forcefields were scaled using scaling factors 0.938, 0.956 and 0.919 for bond stretches, angle bends and torsions respectively.† Scaling the forcefields was found to have little affect on the vibrational amplitude values.

Gas-phase electron diffraction (GED)

Sample preparation. The sample of 4,6-dichloropyrimidine was a gift from Dr R. V. H. Jones of Zeneca plc. Both 2,6-dichloropyrazine and 3,6-dichloropyridazine were bought from Lancaster Synthesis at 99 and 98% purity and used in the GED analysis without further purification.

GED experiments. Electron scattering intensities were recorded on Kodak Electron Image photographic plates using the Edinburgh apparatus.[15] Six plates (three from the long camera distance and three from the short distance) were recorded for each compound and traced digitally using a computer controlled Joyce Loebl MDM6 microdensitometer[16] at the EPSRC Daresbury laboratory. Standard programs were used for the data reduction[17] with the scattering factors of Fink *et al.*[18] The weighting points used in setting up the off-diagonal weight matrix, *s* range, scale factors, correlation parameters and electron wavelengths are given in Table 1. Least-squares correlation matrices for the restrained GED refinement for the compounds under study have been supplied

† Scale constants were obtained from the successful scaling of the forcefield for 1,3,5-triazine against a set of experimental IR frequencies.

Table 1 GED experimental conditions

Compound	T/K		Camera distance /mm	Weighting functions/nm^{-1}					Correlation parameter	Scale factor k [a]	Electron wavelength [b] /pm
	Sample	Nozzle		Δs	s_{min}	s_1	s_2	s_{max}			
4,6-Dichloropyrimidine	400	400	95.42	4	100	120	304	356	0.0855	0.972(24)	0.057 10
			255.02	2	20	40	130	150	0.4339	0.841(4)	0.057 10
2,6-Dichloropyrazine	424	443	97.41	4	120	140	304	356	0.1520	0.899(29)	0.056 74
			257.98	2	20	40	148	158	0.4668	0.940(12)	0.056 72
3,6-Dichloropyridazine	440	442	97.41	4	120	140	304	356	0.3560	0.832(44)	0.056 75
			257.98	2	20	40	140	164	0.4796	0.876(16)	0.056 73

[a] Figures in parentheses are the estimated standard deviations. [b] Determined by reference to the scattering patterns of benzene vapour.

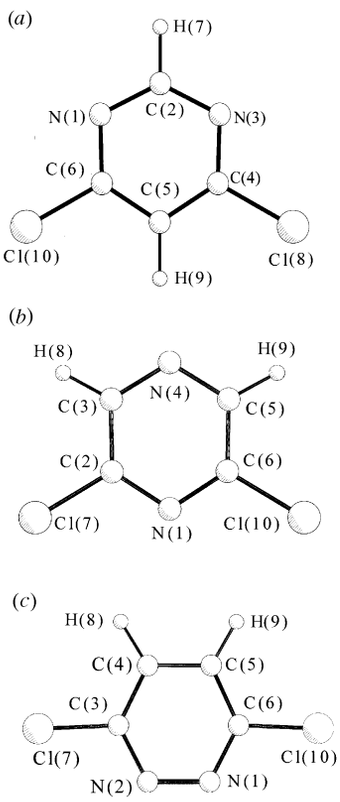

Fig. 1 The structures of (*a*) 4,6-dichloropyrimidine, (*b*) 2,6-dichloropyrazine and (*c*) 3,6-dichloropyridazine

as Supplementary Material (Suppl. Pub. 57228, 4 pp.) from the British Library.‡

GED models. 4,6-*Dichloropyrimidine*.—[Fig. 1(*a*)]. Assuming C_{2v} symmetry, nine independent geometric parameters are required to define the structure completely. They are the average ring bond distance (p_1), the difference between rC–C and mean rC–N bond distance (p_2), r[C(6)–N(1)] minus r[C(2)–N(1)] (p_3), the average C–H distance and r[C(5)–H(9)] minus r[C(2)–H(7)] (p_4 and p_5), rC–Cl (p_6), the internal ring angles ∠NCN (p_7) and ∠CNC (p_8) and, finally, the external ring angle ∠NCCl (p_9).

2,6-*Dichloropyrazine*.—[Fig. 1(*b*)]. Assuming C_{2v} symmetry nine geometric parameters are sufficient to determine the structure of the molecule: the average ring bond distance (p_1), the difference between rC–C and mean rC–N bond distance (p_2), r[C(2)–N(1)] minus r[C(3)–N(4)] (p_3), rC–Cl (p_4), rC–H (p_5), the two internal ring angles ∠C(3)N(4)C(5) (p_6) and ∠N(4)C(5)C(6) (p_7), and the two external ring angles ∠CCCl (p_8) and ∠CCH (p_9).

3,6-*Dichloropyridazine*.—[Fig. 1(c)]. Assuming C_{2v} symmetry, the structure is completely defined by ten independent geometrical parameters, namely the average ring distance (p_1), r[C(3)–C(4)] minus r[C(4)–C(5)] (p_2), rN–N minus rC–N (p_3), the difference between the average rC–C bond distance and the average (rC–N, rN–N) bond distance (p_4), rC–Cl (p_5), rC–H (p_6), ∠NNC (p_7), ∠NCC (p_8), ∠CCCl (p_9) and ∠C(5)C(4)H(8) (p_{10}).

X-Ray crystallography

Crystal Data. See Table 2(*a*).

Data collection and processing. See Table 2(*b*). Stoë Stadi-4 diffractometer equipped with an Oxford Cryosystems variable-temperature device;[19] ω-θ mode, graphite monochromated Cu-Kα, Mo-Kα radiation.

Structure solution and refinement. See Table 2(*c*). Following data reduction and the application of azimuthal scans-based absorption corrections the structures were solved by automatic direct methods[20] to identify the positions of all non-H atoms. Iterative cycles of least-squares refinement and difference Fourier syntheses located the hydrogen atoms.[21] All non-H atoms were refined anisotropically and H atoms isotropically. Corrections for secondary extinction[21] refined to values given in Table 2(*c*). Weighting schemes adopted for the three systems were: $w^{-1} = [\sigma^2(F_o^2) + (0.1246P)^2 + 0.9949P]$ where $P = \frac{1}{3}[\mathrm{MAX}(F_o^2,0) + 2F_o^2]$, $w^{-1} = [\sigma^2(F_o^2) + (0.0590P)^2 + 0.08P]$ and $w^{-1} = [\sigma^2(F_o^2) + (0.1370P)^2 + 0.00P]$ for 4,6-dichloropyrimidine, 2,6-dichloropyrazine and 3,6-dichloropyridazine, respectively.

Atomic coordinates, thermal parameters, and bond lengths and angles have been deposited at the Cambridge Crystallographic Data Centre (CCDC).§

Results and discussion

Ab initio calculations

For each compound a set of calculations, with various basis sets and both including and excluding electron correlation treatment, were performed. The results showed that convergence was effectively reached in each case.

4,6-Dichloropyrimidine and pyrimidine. The results obtained from the series of calculations performed on 4,6-dichloropyrimidine and pyrimidine are given in Table 3; the atom numbering system is shown in Fig. 1(*a*).

In general, geometrical parameter values for 4,6-dichloropyrimidine were largely unaffected by improvements in basis set and level of theory. All bond distances proved to be insensitive to improvements in the basis set beyond 6-31G*; for example, at both the SCF and MP2 levels increasing the size of the basis set to 6-311G** resulted in changes no greater than

‡ For details of the British Library Supplementary Publications scheme see 'Instructions for Authors', *J. Chem. Soc., Perkin Trans. 2*, 1997, Issue 1.

§ For details of the CCDC deposition scheme see 'Instructions for Authors', *J. Chem. Soc., Perkin Trans. 2*, 1997, Issue 1. Any request to the CCDC for this material should quote the full literature citation and the reference number 188/66.

Table 2 X-Ray crystal structures, (*a*) crystal data, (*b*) data collection and processing, (*c*) structure solution and refinement

	Compound		
	4,6-Dichloropyrimidine	2,6-Dichloropyrazine	3,6-Dichloropyridazine
(*a*) Crystal data			
Empirical formula	$C_4H_2N_2Cl_2$	$C_4H_2N_2Cl_2$	$C_4H_2N_2Cl_2$
M	148.98	148.98	148.98
Crystal description	Colourless block	Colourless block	Colourless lath
Crystal size/mm^3	0.66 × 0.51 × 0.19	0.56 × 0.52 × 0.19	0.51 × 0.19 × 0.08
T/K	150	220	220
λ/Å	0.710 73	1.541 84	1.541 84
Crystal system	Monoclinic	Monoclinic	Monoclinic
Space group	$P2_1/c$	$P2_1/c$	$P2_1/c$
Unit cell determination	16 reflections	69 reflections	42 reflections
	$30° \leqslant 2\theta \leqslant 32°$	$40° \leqslant 2\theta \leqslant 44°$	$40° \leqslant 2\theta \leqslant 44°$
	Measured at $\pm\omega$	Measured at $\pm\omega$	Measured at $\pm\omega$
Unit cell dimensions *a*,*b*,*c*/Å, β/°	*a* = 9.702(8)	*a* = 7.277(13)	*a* = 3.8708(13)
	b = 3.780(7)	*b* = 10.972(3)	*b* = 21.091(4)
	c = 97.99(14)	*c* = 7.235(13)	*c* = 14.262(3)
	β = 31.42(4)	β = 90.21(4)	β = 90.282(11)
U/Å	1141(3)	577.7(4)	1164.3(5)
Z	8	4	8
D_c/g cm^{-3}	1.734	1.713	1.700
μ/mm^{-1}	1.011	9.13	9.06
F(000)	592	296	592
(*b*) Data collection and processing			
X-Ray source	Mo	Cu	Cu
Unique reflections	2025	856	1718
Index ranges	$-11 \leqslant h \leqslant 11$	$-8 \leqslant h \leqslant 8$	$-4 \leqslant h \leqslant 4$
	$0 \leqslant k \leqslant 4$	$-12 \leqslant k \leqslant 12$	$-20 \leqslant k \leqslant 23$
	$0 \leqslant l \leqslant 37$	$-8 \leqslant l \leqslant 8$	$-4 \leqslant l \leqslant 16$
θ range	$5° \leqslant 2\theta \leqslant 50°$	$12° \leqslant 2\theta \leqslant 120°$	$8° \leqslant 2\theta \leqslant 120°$
R_{int}	—	0.11	0.04
(*c*) Structure solution and refinement			
Absorption correction T_{min}/T_{max}	0.518/0.474	0.090/0.008	0.103/0.015
Secondary extinction correction	0.008(3)	0.0021(9)	—
R_1 [$F \geqslant 4\sigma(F)$]	0.0588	0.0421	0.0646
wR_2 [all data]	0.172	0.1163	0.1939
$S[F^2]$	1.078	1.116	1.037
No. refining parameters	162	82	149
$(\Delta/\sigma)_{max}$	−0.001	0.0	0.015
Final ΔF synthesis no feature outwith	$+0.62 \longrightarrow -0.95$ e Å^{-3}	$+0.35 \longrightarrow -0.32$ e Å^{-3}	$+0.49 \longrightarrow -0.30$ e Å^{-3}

0.2 pm. Similarly, the four internal ring angles and the one external ring angle, ∠NCCl, changed by less than 0.2° at SCF and 0.3° at MP2 for this basis set improvement. As expected for an aromatic system, electron correlation was found to be important, resulting in the three ring bond distances increasing by *ca.* 2 pm. Electron correlation was also found to affect the two C–H distances, both increasing by *ca.* 1.5 pm. The C–Cl distance was affected less, lengthening by just 0.4 pm. On the inclusion of electron correlation the four internal ring angles changed by less than 1°; angle NCCl remained unchanged. The 6-31+G*/MP2 calculation, performed to assess the effects of diffuse functions on the heavy atoms C, N and Cl, gave results very little different from those obtained in the 6-31G*/MP2 calculation, indicating that these additional functions have a negligible effect. Bond distances varied, on average, by just 0.1 pm, angles by 0.1°.

Parameter values for pyrimidine were also largely unaffected by improvements in basis set and treatment of electron correlation. Improvements in basis set treatment beyond 6-31G* at MP2 level resulted in changes of less than 0.2 pm for all bond distances and less than 0.2° for all angles. Electron correlation effects were again found to be important, with the three ring distances increasing by *ca.* 2 pm, the three C–H distances by 1.3 pm and all angles changing by less than 1°.

2,6-Dichloropyrazine and pyrazine. The results obtained from the series of geometry optimisation calculations for 2,6-dichloropyrazine and pyrazine are given in Table 4 and the molecular framework is shown in Fig. 1(*b*).

In general the trends in geometry observed in the 4,6-dichloropyrimidine series of calculations were also observed for 2,6-dichloropyrazine. The two molecules are electronically similar, since both aromatic rings comprise two C–N distances and one C–C distance. Note that the 6-311G**/SCF and 6-31+G*/MP2 calculations were not performed for 2,6-dichloropyrazine because further improvements in basis set treatment without the inclusion of electron correlation, and the addition of diffuse functions for the heavy atoms in the molecule, had been found to have little effect on the overall geometry of the previous structure.

Like 4,6-dichloropyrimidine, calculated bond distances proved to be rather insensitive to the details of the basis set, with improvements from 6-31G* to 6-311G** at the MP2 level of theory resulting in average changes of 0.2 pm for the three ring bond distances and the two external ring distances, *r*C–Cl and *r*C–H. Similarly, changes in the four internal ring angles and the two external ring angles, ∠CCCl and ∠CCH, were found to be small, averaging just 0.2°. The introduction of electron correlation also resulted in similar changes to those observed for 4,6-dichloropyrimidine, with the three aromatic ring bond distances increasing by *ca.* 2 pm, *r*C–H by *ca.* 1.5 pm, and the C–Cl distance by just 0.1 pm. Electron correlation resulted in changes in the four internal ring angles not exceeding 1°. The two external ring angles were found to be much less affected, with ∠CCCl narrowing by 0.1° and ∠CCH remaining unchanged.

The molecular structure of pyrazine also rapidly converged

Table 3 *Ab initio* molecular geometries (r_e/pm, ∠/°) and energies (Hartrees) for 4,6-dichloropyrimidine and pyrimidine

	Basis Set/Level of theory					
Parameter	3-21G*/SCF	6-31G*/SCF	6-311G**/SCF	6-31G*/MP2	6-31+G*/MP2	6-311G**/MP2
4,6-Dichloropyrimidine						
r[N(1)–C(2)]	132.9	131.8	131.6	134.2	134.3	134.0
r[N(1)–C(6)]	131.8	130.9	130.7	133.2	133.4	133.0
r(C–C)	138.0	138.2	138.0	139.3	139.4	139.4
r[C(2)–H(7)]	106.5	107.3	107.4	108.7	108.6	108.6
r[C(5)–H(9)]	106.6	107.0	106.9	108.4	108.5	108.3
r(C–Cl)	172.8	172.7	172.9	173.1	172.8	172.8
∠NCN	124.0	126.7	126.7	127.2	127.2	127.5
∠CNC	117.8	115.9	115.9	115.2	115.3	115.1
∠NCC	122.4	123.5	123.6	123.6	123.5	123.5
∠CCC	115.7	114.4	114.3	115.1	115.2	115.3
∠NCCl	118.0	117.2	117.3	117.2	117.1	117.5
Energy	−1174.843 879	−1180.492 093	−1180.593 791	−1181.575 465	−1181.575 710	−1181.741 758
Pyrimidine						
r[N(1)–C(2)]	132.9	131.9		134.2		134.1
r[N(1)–C(6)]	133.2	132.1		134.4		134.2
r(C–C)	138.2	138.2		139.3		139.4
r[C(2)–H(7)]	106.7	107.5		108.8		108.7
r[C(4)–H(8)]	107.0	107.6		108.9		108.8
r[C(5)–H(9)]	106.9	107.3		108.6		108.5
∠NCN	124.6	126.9		127.4		127.6
∠CNC	117.7	116.2		115.6		115.5
∠NCC	121.5	122.3		122.3		122.2
∠CCC	116.9	116.0		116.9		116.8
∠NCH	117.0	116.5		116.3		116.4
Energy	−261.206 190	−262.693 488		−263.509 482		−263.625 609

Table 4 *Ab initio* molecular geometries (r_e/pm, ∠/°) and energies (Hartrees) for 2,6-dichloropyrazine

	Basis set/Level of theory			
Parameter	3-21G*/SCF	6-31G*/SCF	6-31G*/MP2	6-311G**/MP2
2,6-Dichloropyrazine				
r(C–C)	138.1	138.6	139.9	140.1
r[C(2)–N(1)]	131.8	130.7	133.3	133.1
r[C(3)–N(4)]	132.8	131.6	134.1	134.0
r(C–Cl)	172.6	172.8	172.9	172.6
r(C–H)	106.6	107.2	108.7	108.5
∠C(3)N(4)C(5)	119.4	118.2	117.0	116.6
∠C(2)C(3)N(4)	119.6	120.2	120.9	121.0
∠N(1)C(2)C(3)	121.3	122.4	123.0	123.1
∠C(2)N(1)C(6)	118.7	116.6	115.4	115.2
∠CCCl	120.2	119.8	119.7	119.4
∠CCH	121.8	121.4	121.4	121.2
Energy	−1174.833 506	−1180.478 452	−1181.567 169	−1181.733 202
Pyrazine				
r(C–C)	138.1	138.6	139.6	139.8
r(C–N)	133.1	131.9	134.4	134.3
r(C–H)	106.9	107.4	108.8	108.7
∠CNC	118.0	116.6	115.3	115.0
∠NCC	121.0	121.7	122.3	122.5
∠NCH	117.7	117.4	116.6	116.7
Energy	−261.197 500	−262.683 005	−263.503 627	−263.619 887

with improvements in the level of calculation. Improvements in basis set treatment from 6-31G* to 6-311G** at the MP2 level gave rise to changes less than 0.2 pm in all bond lengths and less than 0.3° in all ring angles. Electron correlation again resulted in changes in bond length of the order of 2 pm and in angles by *ca.* 1°.

3,6-Dichloropyridazine and pyridazine. The results of the molecular geometry calculations for 3,6-dichloropyridazine and pyridazine are given in Table 5; the molecular framework is shown in Fig. 1(*c*).

The molecular structure of 3,6-dichloropyridazine is quite distinct from those of 4,6-dichloropyrimidine and 2,6-dichloropyrazine, having four different ring bond distances (C–N, two C–C and N–N), in contrast to just three ring bond distances in the previous two structures. In particular, it is the only one of these compounds to have an N–N bond. As a result the similarities noted in the two previous series of calculations were not repeated. Strong similarities were found, however, for the two external ring bond distances, *r*C–Cl and *r*C–H.

Improvements in basis set from 6-31G* to 6-311G** at the MP2 level resulted in an increase of 0.5 pm for *r*N–N and a smaller change of 0.2 pm for the remaining three ring bond distances and the two external ring distances C–Cl and C–H.

Table 5 *Ab initio* molecular geometries (r_e/pm, ∠/°) and energies (Hartrees) for 3,6-dichloropyridazine and pyridazine

Parameter	Basis set/Level of theory			
	3-21G*/SCF	6-31G*/SCF	6-31G*/MP2	6-311G**/MP2
4,6-Dichloropyridazine				
r[C(3)–C(4)]	139.9	140.1	140.1	140.2
r[C(4)–C(5)]	135.8	136.0	138.2	138.4
r(C–N)	130.0	129.4	133.5	133.3
r(N–N)	136.1	131.7	134.9	134.4
r(C–Cl)	173.0	172.9	172.7	172.5
r(C–H)	106.8	107.2	108.6	108.4
∠NNC	119.3	119.8	118.8	118.9
∠NCC	123.6	123.8	124.5	124.6
∠CCC	117.1	116.4	116.7	116.5
∠CCCl	119.1	119.3	119.7	119.3
∠CCH	120.3	121.0	121.2	121.2
Energy	−1174.793 719	−1180.443 680	−1181.535 211	−1181.700 630
Pyridazine				
r[C(3)–C(4)]	139.5	139.4	139.7	139.9
r[C(4)–C(5)]	136.5	136.8	138.6	138.8
r(C–N)	131.6	131.0	134.4	134.3
r(N–N)	135.6	131.0	134.8	134.2
r[C(3)–H(7)]	106.9	107.4	108.7	108.6
r[C(4)–H(8)]	107.0	107.4	108.6	108.5
∠NNC	119.4	120.0	119.0	119.1
∠NCC	123.2	123.3	124.1	124.2
∠CCC	117.4	116.7	116.9	116.8
∠NCH	115.9	115.4	114.4	114.4
Energy	−261.159 689	−262.650 029	−263.474 317	−263.590 143

Table 6 *Ab initio* geometric parameter restraints (r_e/pm, ∠/°)

Compound		Parameter	Basis set/Level of theory				
			3-21G*/SCF	6-31G*/SCF	6-31G*/MP2	6-311G**/MP2	Restraint
4,6-Dichloropyrimidine	p_2	*r*(C–C) − av. *r*(C–N)	5.6	6.8	5.6	5.9	5.9(9)
	p_3	diff. *r*(C–N)	−1.0	−0.8	−0.9	−1.0	−1.0(2)
	p_4	av. *r*(C–H)	106.5	107.1	108.5	108.4	108.4(15)
	p_5	diff. *r*(C–H)	0.1	−0.4	−0.3	−0.3	−0.3(1)
2,6-Dichloropyrazine	p_2	*r*(C–C) − av. *r*(C–N)	5.8	7.5	6.2	6.5	6.5(10)
	p_3	diff. *r*(C–N)	−1.1	−0.9	−0.8	−0.8	−0.8(1)
	p_5	*r*(C–H)	106.6	107.2	108.7	108.5	108.5(15)
	p_9	∠CCH	121.7	121.4	121.4	121.2	121.2(15)
	p_6-p_7	∠C(3)N(4)C(5) − ∠C(2)C(3)N(4)	−0.2	−2.0	−3.9	−4.4	−4.4(5)
3,6-Dichloropyridazine	p_2	diff. *r*(C–C)	4.1	4.2	1.9	1.9	1.9(1)
	p_3	*r*(N–N) − *r*(C–N)	6.1	2.3	1.4	1.1	1.1(3)
	p_4	av. *r*(C–C) − av. [*r*(N–N), *r*(C–N)]	6.5	8.6	5.5	6.0	6.0(5)
	p_6	*r*(C–H)	106.8	107.2	108.6	108.4	108.4(15)
	p_{10}	∠CCH	120.3	121.0	121.2	121.2	121.2(15)

Values observed for the three internal ring angles and external ring angle ∠CCCl changed by less than 0.2° and 0.4°, respectively. Angle CCH remained unchanged for this basis set improvement. Electron correlation effects using the 6-31G* basis set resulted in changes of *ca.* 3 pm for *r*N–N, 4 pm for *r*C–N and 2 pm for one of the *r*C–C distances, with the remaining *r*C–C distance unchanged. All ring angle changes due to electron correlation were observed to be less than 1°. Changes recorded in the two external ring angles were 0.4° and 0.2° for ∠CCCl and ∠CCH respectively.

Finally, the geometric parameters of pyridazine also successfully converged with improvements in basis set and treatment of electron correlation. Improving the basis set beyond 6-31G* at the MP2 level gave rise to changes of the order 0.2 pm for all distances with the exception of *r*N–N, which shortened by 0.6 pm. All angles were also seen to converge to within 0.1°. In results closely paralleling those observed for 3,6-dichloropyridazine, electron correlation to the MP2 level was seen to increase the N–N distance by *ca.* 5 pm, *r*C–N by *ca.* 3 pm and one of the C–C distances by *ca.* 2 pm, with the remaining C–C distances unchanged. All angle changes due to electron correlation were observed to be less than 1°.

Gas-phase electron diffraction (GED) restrained refinement results

The geometric restraints required to complete the structural refinements, given in Table 6, were derived from the range of *ab initio* calculations performed, in accordance with the SARACEN method.[3] In each case values for restraints are taken from the highest level calculation (*i.e.* 6-311G**/MP2) and uncertainty ranges usually estimated from a consideration of values given by the other lower level calculations, based on a working knowledge of the reliability of the calculations from a study of electronically similar systems. Restraints were also applied to ratios of vibrational amplitude values for electronically similar bond distances lying close together on the radial distribution curve. Values for amplitude restraints, described in Table 7, were calculated directly from the scaled *ab initio* force-field and uncertainty ranges of 5% were adopted. These restraints enabled the refinement of vibrational amplitude

Table 7 *Ab initio* vibrational amplitude restraints

Compound	Amplitude ratio	Value[a]	Uncertainty[b]
4,6-Dichloropyrimidine	u_2[C(4)–N(3)]/u_1[N(1)–C(2)]	1.004	0.050
	u_3[C(4)–C(5)]/u_1[N(1)–C(2)]	1.038	0.052
	u_{10}[N(1)···C(5)]/u_8[N(1)···N(3)]	1.033	0.052
	u_{12}[C(4)···C(6)]/u_{11}[C(2)···C(4)]	1.035	0.052
	u_{14}[Cl(8)···C(5)]/u_9[N(1)···Cl(10)]	1.044	0.052
	u_{16}[C(2)···C(5)]/u_{15}[N(1)···C(4)]	0.972	0.049
	u_{19}[C(4)···Cl(10)]/u_{17}[C(2)–Cl(8)]	1.019	0.051
2,6-Dichloropyrazine	u_2[C(3)–N(4)]/u_1[N(1)–C(2)]	0.998	0.050
	u_3[C(2)–C(3)]/u_1[N(1)–C(2)]	1.055	0.053
	u_6[N(1)···C(3)]/u_7[C(2)···N(4)]	1.001	0.050
	u_{11}[N(1)···Cl(10)]/u_{13}[C(3)···Cl(7)]	0.946	0.047
	u_{15}[C(2)···C(5)]/u_{14}[N(1)···N(4)]	0.944	0.047
3,6-Dichloropyridazine	u_2[N(2)–N(3)]/u_1[N(1)–N(2)]	0.966	0.048
	u_4[C(3)–C(4)]/u_1[N(1)–N(2)]	1.041	0.052
	u_6[C(4)–C(5)]/u_1[N(1)–N(2)]	0.974	0.049
	u_8[N(2)···C(4)]/u_7[N(1)···C(3)]	1.022	0.051
	u_9[C(3)···C(5)]/u_7[N(1)···C(3)]	1.053	0.053
	u_{10}[N(2)···Cl(7)]/u_{13}[C(4)···Cl(7)]	0.950	0.047
	u_{15}[C(3)···C(6)]/u_{14}[N(1)···C(4)]	0.961	0.048
	u_{21}[C(5)···Cl(7)]/u_{18}[N(1)···Cl(7)]	1.014	0.051

[a] Values taken from 6-31G*/SCF scaled forcefields. [b] Uncertainties are 5% of the amplitude ratio.

Table 8 GED results for 4,6-dichloropyrimidine (r_a^0/pm, ∠/°)

	Parameter	Restrained GED results[a]
	Independent[b]	
p_1	Av. ring distance	135.2(1)
p_2	r(C–C) − av. r(C–N)	4.6(8)
p_3	diff. r(C–N)	−1.0(2)
p_4	av. r(C–H)	109.2(11)
p_5	diff. r(C–H)	−0.3(1)
p_6	r(C–Cl)	173.1(1)
p_7	∠NCN	127.8(5)
p_8	∠CNC	114.6(4)
p_9	∠NCCl	117.1(4)
	Dependent	
	r(C–C)	138.3(6)
	r[C(2)–N(1)]	134.2(3)
	r[C(6)–N(1)]	133.2(3)
	r[C(2)–H(7)]	109.4(11)
	r[C(5)–H(9)]	109.0(11)
	∠NCC	123.8(3)
	∠CCC	115.4(7)

[a] Estimated standard deviations, obtained in the least-squares refinement, are given in parentheses. [b] For definition of parameters, see the text.

values that would otherwise have to be rigidly tied to refining amplitudes, or remain fixed at the values obtained from the scaled harmonic forcefields.

4,6-Dichloropyrimidine. The results obtained in the structural refinement of 4,6-dichloropyrimidine are presented in Table 8. Of the nine geometrical parameters required to describe the structure fully, five were able to refine freely. The remaining four ($p_{2–5}$) were therefore assigned the *ab initio* based restraints given in Table 6. Similarly, only nine out of a total of 27 vibrational amplitudes (u_2, u_6, u_9, u_{10}, u_{11}, u_{15}, u_{17}, u_{22} and u_{25}) were able to refine unaided. An additional seven amplitudes were successfully refined with the inclusion of the ratio amplitude restraints documented in Table 7, resulting in the vibrational amplitudes of the 16 distances giving rise to the most prominent features on the radial distribution curve being able to refine. The remaining fixed amplitudes of vibration, all for atom pairs involving hydrogen, were considered to have little effect on values or standard deviations of those which were refined.

Final values obtained for the three ring distances were found to be 138.3(6), 134.2(3) and 133.2(3) pm for rC–C, r[C(2)–N(1)] and r[C(6)–N(1)], respectively, agreeing with values calculated by *ab initio* methods (6-311G**/MP2) to within one or two standard deviations. Similarly, a close agreement between experiment and theory was observed for the four internal ring angles, with all values in agreement to within about one experimental standard deviation or 0.5°. The chlorine atoms were readily located by the GED data, with p_6 (C–Cl distance) refining to 173.1(1) pm and p_9 (∠NCCl) refining to 117.4(1)°, compared to the *ab initio* values of 172.8 pm and 117.5°. The hydrogen atoms were also successfully found with the aid of restraints, enabling r[C(2)–H(7)] and r[C(5)–H(9)] to refine to 109.4(11) and 109.0(11) pm, compared to their respective *ab initio* values of 108.6 and 108.3 pm.

The R_G factor for this refinement was 8.5%, indicating that the data are of good quality. With all nine geometric parameters and 16 vibrational amplitudes refining, the structure is the best that can be obtained using all available data, both experimental and theoretical, and all standard deviations should be reliable estimates, free from systematic errors due to limitations of the model. The full list of bond distances and vibrational amplitudes is given in Table 9. The final combined molecular scattering curve and radial distribution curve are given in Figs. 2(*a*) and 3(*a*) respectively.

2,6-Dichloropyrazine. The results obtained for the structural refinement of 2,6-dichloropyrazine are given in Table 10. The five geometric restraints required to allow all geometric parameters to refine to realistic values are given in Table 6. Of the 25 vibrational amplitudes, only nine successfully refined unassisted, namely u_1, u_5, u_7, u_{11}, u_{15}, u_{16}, u_{19}, u_{22} and u_{24}. A further five vibrational amplitudes were refined with the introduction of five ratios of vibrational amplitude, documented in Table 7.

The three ring distances refined to 139.1(4), 134.3(2) and 133.4(2) pm for rC–C, r[C(3)–N(4)] and r[C(2)–N(1)], respectively, within two or three standard deviations of results obtained from the 6-311G**/MP2 calculation. The four internal ring angles also refined to values concordant with those predicted from the 6-311G**/MP2 calculation, with experiment and theory in agreement to within 1°, or three standard deviations. The chlorine atom positions were well defined, with rC–Cl (p_4) refining to 173.5(2) pm and ∠CCCl (p_8) to 120.0(3)°, compared to the values 172.6 pm and 119.4° calculated *ab initio*. The two parameters defining the hydrogen atom positions (p_5, rC–H and p_9, ∠CCH) were successfully restrained, refining to 108.2(12) pm and 122.8(13)°, compared to 108.5 pm and 121.2° from the 6-311G**/MP2 calculation.

The final R_G factor recorded for this refinement was 9.3%.

Table 9 Interatomic distances (r_a/pm) and amplitudes of vibration (u/pm) for the restrained GED structure of 4,6-dichloropyrimidine[a]

i	Atom pair	Distance	Amplitude[b]
1	N(1)–C(2)	134.4(2)	5.1(3)
2	C(4)–N(3)	133.3(3)	5.2(3)
3	C(4)–C(5)	138.5(6)	5.1(3)
4	C(2)–H(7)	110.4(11)	7.4 (fixed)
5	C(5)–H(9)	110.3(11)	7.4 (fixed)
6	C(4)–Cl(8)	173.4(2)	4.9(2)
7	N(1)···H(7)	207.8(9)	9.2 (fixed)
8	N(1)···N(3)	241.4(7)	5.8(5)
9	N(1)···Cl(10)	262.1(5)	7.4(3)
10	N(1)···C(5)	239.9(6)	6.0(5)
11	C(2)···C(4)	225.1(4)	4.5(8)
12	C(4)···C(6)	234.0(6)	4.7(9)
13	C(4)···H(9)	217.8(12)	9.4 (fixed)
14	Cl(8)···C(5)	269.2(4)	7.7(4)
15	N(1)···C(4)	272.2(5)	8.7(12)
16	C(2)···C(5)	266.2(12)	8.5(12)
17	C(2)···Cl(8)	384.6(4)	9.4(5)
18	N(1)···H(9)	339.0(12)	9.0 (fixed)
19	C(4)···Cl(10)	394.5(5)	9.3(5)
20	C(4)···H(7)	323.9(11)	8.9 (fixed)
21	Cl(8)···H(9)	287.3(8)	13.3 (fixed)
22	N(1)···Cl(8)	445.2(5)	10.1(5)
23	C(2)···H(9)	375.8(16)	8.8 (fixed)
24	C(5)···H(7)	376.0(16)	8.8 (fixed)
25	Cl(8)···Cl(10)	537.4(7)	12.0(6)
26	Cl(8)···H(7)	469.4(10)	10.2 (fixed)
27	H(7)···H(9)	485.3(24)	11.1 (fixed)

[a] Estimated standard deviations, obtained in the least-squares refinement, are given in parentheses. [b] Amplitudes not refined were fixed at values calculated using the scaled 6-31G*/SCF force field.

Table 10 GED results for 2,6-dichloropyrazine (r_a^0/pm, ∠/°)

	Parameter	Restrained GED results[a]
	Independent[b]	
p_1	Av. ring distance	135.6(1)
p_2	r(C–C) − av. r(C–N)	5.2(6)
p_3	diff. r(C–N)	−0.8(1)
p_4	r(C–Cl)	173.5(2)
p_5	r(C–H)	106.1(2)
p_6	∠C(3)N(4)C(5)	117.2(2)
p_7	∠C(2)C(3)N(4)	120.4(2)
p_8	∠CCCl	120.0(3)
p_9	∠CCH	119.3(14)
	Dependent	
	r(C–C)	139.1(4)
	r[C(3)–N(4)]	134.3(2)
	r[C(2)–N(1)]	133.4(2)
	∠N(1)C(2)C(3)	123.8(3)
	∠C(2)N(1)C(6)	114.4(3)
	∠NCC	123.8(3)
	∠CCC	115.4(7)

[a] Estimated standard deviations, obtained in the least-squares refinement, are given in parentheses. [b] For definition of parameters, see the text.

Since all geometric parameters and the 14 most significant vibrational amplitudes are refining, this structure, obtained by combining experimental and theoretical data, represents the best possible solution that can be obtained at present. The complete list of interatomic distances and amplitudes of vibration determined in this refinement are given in Table 11. The combined molecular scattering intensities and final differences are shown in Fig. (2*b*), and the final radial distribution and difference curves in Fig. 3(*b*).

3,6-Dichloropyridazine. The results obtained for the structural refinement of 3,6-dichloropyridazine are given in Table 12. In addition to the GED data, two sets of rotation constants

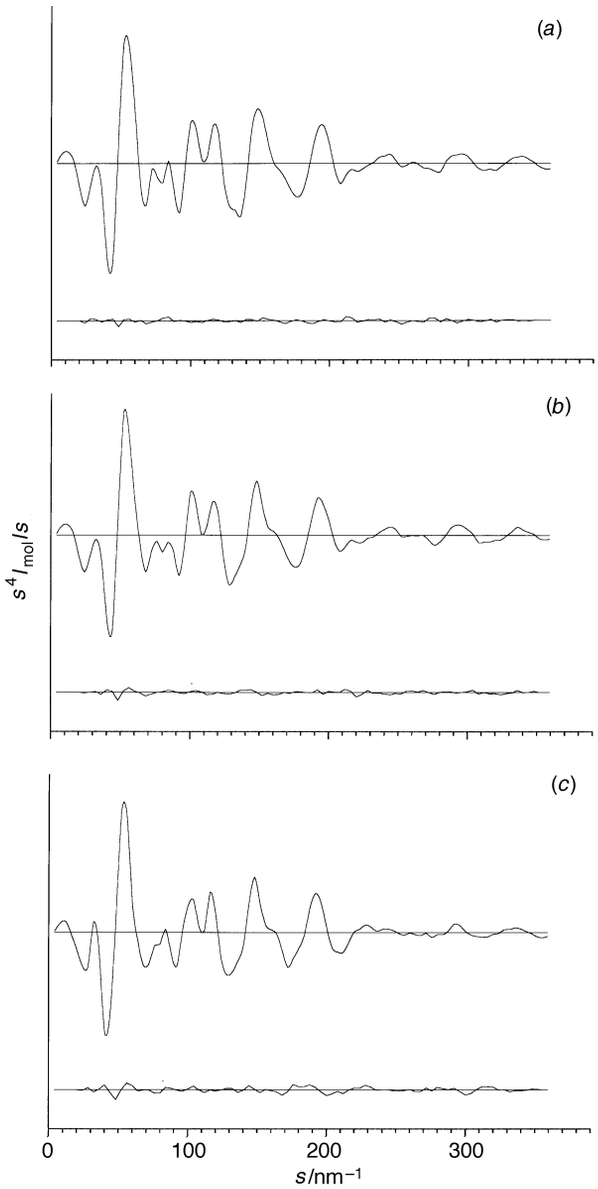

Fig. 2 Observed and final difference combined molecular scattering curves for (*a*) 4,6-dichloropyrimidine, (*b*) 2,6-dichloropyrazine and (*c*) 3,6-dichloropyridazine

were available for this compound,[22] the first set corresponding to the ^{35}Cl/^{35}Cl isotopomer and the second to ^{35}Cl/^{37}Cl. The structural refinement therefore comprises a combination of GED data, six rotation constants and five geometric restraints (documented in Table 6), resulting in a structure with all geometric parameters refining. In addition, eight amplitude ratios were restrained (see Table 7), enabling a total of 16 amplitudes of vibration to refine.

To account for the change in bond distance incurred upon isotopic substitution, an extra parameter was written into the model: p_{11} is defined as r(C–^{37}Cl) minus r(C–^{35}Cl). Although the refined value of this parameter was found to be consistently zero, its inclusion avoided systematic under-estimation of standard deviations for other parameters with which it might be correlated. The vibrational corrections required to convert the rotation constant data from the experimental structure type B_o to B_z (equivalent to the r_a^0 structural type derived from the GED data) were obtained from the scaled *ab initio* forcefield. Values for rotation constants, along with the vibrational corrections and calculated values based on the structure obtained, are given in Table 13. Note that the uncertainties, used to weight the data, are based on assumed experimental errors of 1 MHz for rota-

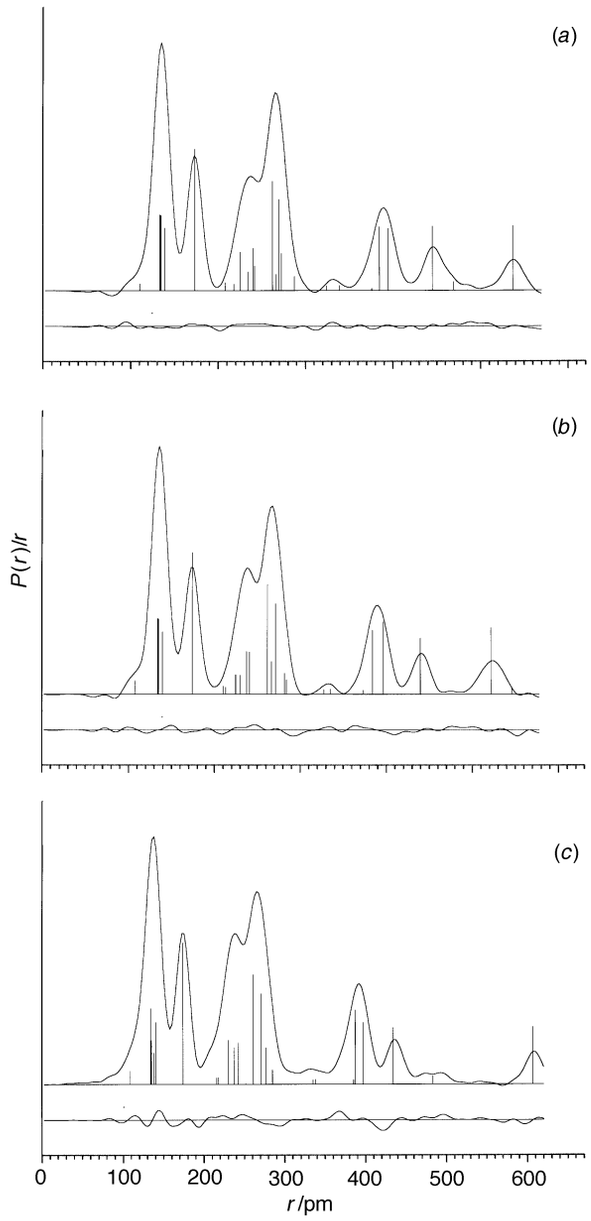

Fig. 3 Observed and final difference radial-distribution curves for (*a*) 4,6-dichloropyrimidine, (*b*) 2,6-dichloropyrazine and (*c*) 3,6-dichloropyridazine. Before Fourier inversion the data were multiplied by $s.\exp(-0.000\ 02s^2)/(Z_{Cl} - f_{Cl})(Z_C - f_C)$

tion constant *A* and 0.1 MHz for *B* and *C*, plus a conservative estimate of 10% error in the vibrational corrections.

The four ring distances refined to values in agreement with those obtained from the 6-311G**/MP2 calculation to within one standard deviation, with *r*N–N refining to 134.2(3), *r*C–N to 133.0(3) pm and the two C–C distances to 138.1(3) and 140.0(3) pm. The three internal ring angles were also found to agree well with theory, with all three angles consistent with the 6-311G**/MP2 results to within 0.5°. The chlorine atoms positions were satisfactorily determined, with *r*C–Cl (p_5) refining to 173.1(2) pm and ∠CCCl (p_9) to 119.1 (14)°, compared to the *ab initio* values of 172.5 pm and 119.3°. The hydrogen atoms were also successfully located with the aid of restraints, enabling *r*C–H (p_6) to refine to 108.2(12) pm and ∠[C(5)C(4)H(8)] (p_{10}) to 122.8(13)°, compared to the *ab initio* values of 108.4 pm and 121.2°.

The final R_G factor for this refinement was 13.5%. The complete list of interatomic distances and amplitudes of vibration is given in Table 14. The combined molecular scattering intensities and final differences are shown in Fig. 2(*c*) and the final radial distribution and difference curves in Fig. 3(*c*).

Table 11 Interatomic distances (r_a/pm) and amplitudes of vibration (*u*/pm) for the restrained GED structure of 2,6-dichloropyrazine[a]

i	Atom pair	Distance	Amplitude[b]
1	N(1)–C(2)	133.6(2)	5.0(3)
2	C(3)–N(4)	134.5(3)	5.0(3)
3	C(2)–C(3)	139.3(4)	5.3(4)
4	C(3)–H(8)	107.3(11)	7.4 (fixed)
5	C(2)–Cl(7)	173.8(2)	5.3(3)
6	N(1)···C(3)	240.7(4)	5.3(3)
7	C(2)···N(4)	237.4(3)	5.3(4)
8	C(2)···C(6)	224.5(4)	5.0 (fixed)
9	C(3)···C(5)	229.6(4)	5.0 (fixed)
10	N(4)···H(8)	209.7(17)	9.3 (fixed)
11	N(1)···Cl(10)	261.7(3)	8.0(5)
12	C(2)···H(8)	213.0(18)	9.4 (fixed)
13	C(3)···Cl(7)	271.3(5)	7.8(5)
14	N(1)···N(4)	281.5(4)	5.0(11)
15	C(2)···C(5)	266.3(3)	4.8(10)
16	N(4)···Cl(10)	396.3(4)	7.9(5)
17	N(1)···H(8)	335.0(14)	9.0 (fixed)
18	H(8)···Cl(7)	284(2)	13.0 (fixed)
19	C(2)···Cl(10)	383.7(3)	7.2(6)
20	H(8)···C(5)	327.4(14)	9.0 (fixed)
21	H(8)···H(9)	417(3)	12.3 (fixed)
22	Cl(10)···Cl(7)	521.7(6)	11.2(6)
23	H(8)···C(6)	372.7(12)	8.8 (fixed)
24	Cl(7)···C(5)	439.5(2)	8.1(5)
25	H(8)···Cl(10)	545.8(12)	8.9 (fixed)

[a] Estimated standard deviations, obtained in the least-squares refinement, are given in parentheses. [b] Amplitudes not refined were fixed at values calculated using the scaled 6-31G*/SCF forcefield.

Table 12 GED results for 2,6-dichloropyridazine (r_a^0/pm, ∠/°)

	Parameter	Restrained GED + rotation constants results[a]
	Independent[b]	
p_1	Av. ring distance	136.4(1)
p_2	diff. *r*(C–C)	1.9(1)
p_3	*r*(N–N) − *r*(C–N)	1.2(3)
p_4	av. *r*(C–C) − av. [*r*(N–N), *r*(N–C)]	6.0(5)
p_5	*r*(C–Cl)	173.1(2)
p_6	*r*(C–H)	108.2(12)
p_7	∠NNC	118.4(2)
p_8	∠NCC	124.7(4)
p_9	∠CCCl	119.1(14)
p_{10}	∠CCH	122.8(13)
p_{11}	*r*[(C–^{37}Cl) − (C–^{35}Cl)]	0.00(6)
	Dependent	
	r[C(5)–C(6)]	140.0(3)
	r[C(4)–C(5)]	138.1(3)
	r(C–N)	133.0(3)
	r(N–N)	134.2(3)
	∠CCC	116.9(3)

[a] Estimated standard deviations, obtained in the least-squares refinement, are given in parentheses. [b] For definition of parameters, see the text.

Effects of chlorination on ring geometry

The gas-phase molecular structures of the dichloro derivatives of pyrimidine, pyrazine and pyridazine were compared to those of their respective parent molecules to determine the effects of electron-withdrawing substituents on the overall ring geometry. In addition to the structures of the three dichloro derivatives presented in this paper a fourth, 2,5-dichloropyrimidine, which had been published previously,[3] was also considered in this investigation.

The observed changes in ring geometry are presented in Table 15, where most structural trends identified by experiment are also clearly present in the structures calculated *ab initio*. In addition the trends observed are consistent with

Table 13 Rotation constants (B/MHz) for 3,6-dichloropyridazine as used in the gas-phase structure study

Rotation constant		Observed		Calculated	Difference	
Species	Axis	B_o	B_z	B_z	B_z(Obs. − Calc.)	Uncertainty
$^{35}Cl/^{35}Cl$	A	5916.6(10)	5917.2(12)	5917.1	0.1	1.2
	B	710.02(10)	709.94(12)	709.94	0.0	0.12
	C	634.00(10)	633.94(12)	633.89	0.05	0.12
$^{37}Cl/^{35}Cl$	A	5916.1(10)	5916.7(12)	5916.8	0.1	1.2
	B	692.40(10)	692.33(12)	692.35	0.02	0.12
	C	619.90(10)	619.84(12)	619.82	0.02	0.12

Table 14 Interatomic distances (r_a/pm) and amplitudes of vibration (u/pm) for the restrained structure of 2,6-dichloropyridazine[a]

i	Atom pair	Distance/pm	Amplitude[b]/pm
1	N(1)–N(2)	134.3(3)	5.5(4)
2	N(2)–C(3)	133.1(3)	5.5(4)
3	C(3)–Cl(7)	173.6(2)	4.4(4)
4	C(3)–C(4)	140.1(3)	5.3(5)
5	C(4)–H(8)	108.5(13)	9.4 (fixed)
6	C(4)–C(5)	138.3(3)	5.2(4)
7	N(1)···C(3)	229.7(3)	4.6(6)
8	N(2)···C(4)	242.0(4)	4.7(6)
9	C(3)···C(5)	237.1(6)	4.9(6)
10	N(2)···Cl(7)	261.1(15)	7.8(12)
11	C(3)···H(8)	216.2(16)	9.0 (fixed)
12	C(5)···H(8)	218.1(18)	7.4 (fixed)
13	C(4)···Cl(7)	270.7(20)	8.3(13)
14	N(1)···C(4)	276.6(6)	6.5(13)
15	C(3)···C(6)	260.9(4)	6.3(13)
16	Cl(7)···H(8)	285(3)	10.2 (fixed)
17	H(9)···H(8)	252(5)	15.1 (fixed)
18	N(1)···Cl(7)	386.8(11)	8.4(11)
19	C(3)···H(9)	335.6(15)	9.5 (fixed)
20	N(2)···H(8)	338.3(13)	9.0 (fixed)
21	C(5)···Cl(7)	396.9(16)	7.9(11)
22	N(1)···H(8)	385.1(12)	9.1 (fixed)
23	C(6)···Cl(7)	433.9(2)	8.6(7)
24	Cl(10)···H(8)	483.3(22)	13.3 (fixed)
25	Cl(7)···Cl(10)	606.6(1)	10.0(6)

[a] Estimated standard deviations, obtained in the least-squares refinement, are given in parentheses. [b] Amplitudes not refined were fixed at values calculated using the scaled 6-31G*/SCF forcefield.

observations from previous studies of dichloro derivatives of benzene.[23–26] The main structural changes can be summarised as widening of the *ipso* ring angle, narrowing of the adjacent ring angles and shortening of the adjacent C–C/C–N bonds, with the C–N bonds more sensitive to change than the C–C bonds. These effects were found to be particularly pronounced for 4,6-dichloropyrimidine and 2,6-dichloropyrazine since the chlorine substituents are *meta* with respect to each other, resulting in additive effects. The structural trends observed can be readily explained in terms of bonding hybridisation effects: since chlorine withdraws electron density from the ring an increase in p character of the *ipso* carbon sp^2 hybrid orbital will be required along the direction of the C–Cl bond. This will effectively lead to a decrease in p character of the remaining sp^2 orbitals, and hence gives rise to a widening of the *ipso* angle and shortening of the adjacent C–N/C–C bonds.

Two points regarding the C–C and C–N bonds adjacent to chlorine substituents are worth noting. First, it is interesting to note that whilst from experiment the C–C bonds were found to shorten slightly or be unaffected by the chlorine atom, from *ab initio* calculations the bonds were predicted to either be unaffected or lengthen slightly. The effect is small, however, and values obtained from the two methods are indistinguishable from one another to within one or two standard deviations. Secondly, in all four cases both experiment and *ab initio* calculations predict that C–N distances adjacent to the chlorine substituent are much more sensitive to change than C–C bonds. Moreover, for all four molecules the two methods show that the C–N bonds shorten, in contrast to the C–C bonds which were found to be only slightly shortened or lengthened by the presence of the chlorine substituent. One possible explanation for this difference in behaviour lies with the lone pair of electrons on the nitrogen atom. The chlorine atom withdraws electron density from the carbon atom, which will therefore acquire a net positive charge. The lone pair on the neighbouring nitrogen atom will then be attracted towards the carbon atom, thereby increasing the bond order (and thus reducing the length) of the C–N bond.

Crystal structure results

Geometric parameters recorded for the three dichloro compounds can be found in Table 16, and crystal packing diagrams in Fig. 4(*a–c*). The structures of the three compounds in the solid phase were found to be planar, with either one or two molecules located in the asymmetric units.

It has long been recognised that the comparison of molecular structures in the gaseous and solid phases is the most direct method to investigate molecular distortions found in the crystal environment.[27] Comparing the geometry of the free molecule with that of the crystal molecule is, however, not straightforward.[28] First, there is a difference in bond length definition between the two techniques, with GED measuring internuclear distances and X-ray crystallography distances between centres of electron density. Since for an aromatic ring the centres of electron density lie just inside the ring (due to π-bonding) the average ring distance will appear to be shorter in the crystal than in the gas. Secondly, structural discrepancies can also be attributed to different vibrational averaging effects in the gaseous and crystal phases, and are therefore also temperature dependent. This is illustrated by an average ring contraction of 2 pm for 2,6-dichloropyrazine and 3,6-dichloropyridazine, where data were collected at a temperature of 220 K, compared with the smaller average contraction of 0.4 pm for 4,6-dichloropyrimidine, for which data were recorded at the lower temperature of 150 K. This ring contraction effect will only cause bond distances to shorten; angles will remain unaffected. For these two reasons we have only attempted to investigate significant structural distortions between the two phases of greater than 3 or 4σ, and for any significant change in bond distance a consideration of average ring contraction for the molecule is also taken into account.

Examples of significant molecular distortions were found for all three compounds and can readily be interpreted in terms of intermolecular bonding (N···H or Cl···Cl interactions) between neighbouring molecules. In the crystal structure of 4,6-dichloropyrimidine [Fig. 4(*a*)], molecules were found to pack as chains linked by C(H)···N and Cl···Cl contacts. The most significant distortions found for the first molecule in the asymmetric unit concerned distances rN(3)C(4) and rC(4)Cl(8), distorting by −2.2(6) and +1.6(4) pm from the gas-phase structure which, taking the ring contraction effect into account, results in relative changes of −1.8(6) and +2.0(4) pm. In the

Table 15 Effects of chlorination on ring geometries[a]

	Parameter							
	Ring angle at Cl substituted carbon		Ring angle at adjacent atom		*r*C–N; carbon Cl substituted		*r*C–C; one carbon Cl substituted	
Molecule	Experiment	*ab initio*	Experiment	*ab initio*	Experiment	*ab initio*	Experiment	*ab initio*
2,5-Dichloropyrimidine	+0.1(5)	+0.3	+0.6(8)	+0.2	−0.3(9)	−0.7	0.0(11)	+0.1
	+0.5(6)	+0.5	−0.6(8)	−0.5				
4,6-Dichloropyrimidine	+2.6(3)	+1.3	−1.1(5)	−0.4	−1.8(8)	−1.2	−1.0(7)	0.0
			−2.4(7)	−1.5				
2,6-Dichloropyrazine	+1.6(5)	+0.6	−1.8(3)	−1.5	−0.4(2)	−1.2	−0.6(5)	+0.3
			−1.2(4)	+0.2				
3,6-Dichloropyridazine	+0.9(4)	+0.4	−1.0(2)	−0.2	−0.8(3)	−0.9	−0.0(3)	+0.3
			0.0(3)	−0.3				

[a] Angles in degrees, distances in pm.

Table 16 Crystal structure parameters for the molecules found in the asymmetric units of 4,6-dichloropyrimidine, 2,6-dichloropyrazine and 3,6-dichloropyridazine (*r*/pm, ∠/°)

	Molecule 1	Molecule 2
4,6-Dichloropyrimidine bond lengths		
r[N(1)–C(2)]/*r*[N(3)–C(2)]	133.8(5), 134.2(5)	132.0(5), 134.6(5)
r[N(1)–C(6)]/*r*[N(3)–C(4)]	131.7(5), 131.0(5)	133.4(5), 133.3(5)
r[C(6)–C(5)]/*r*[C(4)–C(5)]	139.1(5), 138.4(5)	139.1(5), 137.4(5)
r[C(6)–Cl(10)]/*r*[C(4)–Cl(8)]	173.3(4), 174.7(4)	171.3(4), 174.1(4)
Angles		
∠N(1)C(2)N(3)	128.2(3)	125.9(4)
∠C(2)N(1)C(6)/∠C(2)N(3)C(4)	113.5(3), 115.1(3)	115.1(3), 115.9(3)
∠N(1)C(6)C(5)/∠N(3)C(4)C(5)	124.7(3), 123.4(3)	125.6(3), 124.7(3)
∠C(4)C(5)C(6)	114.9(3)	112.8(3)
∠N(1)C(6)Cl(10)/∠N(3)C(4)Cl(8)	115.2(3), 116.6(3)	116.0(3), 117.2(3)
2,6-Dichloropyrazine bond lengths		
r[N(1)–C(2)]/*r*[N(1)–C(6)]	131.2(3), 131.8(3)	
r[C(2)–C(3)]/*r*[C(6)–C(5)]	138.2(4), 137.1(4)	
r[C(3)–N(4)]/*r*[C(5)–N(4)]	132.6(4), 132.5(3)	
r[C(2)–Cl(7)]/*r*[C(6)–Cl(10)]	173.0(3), 173.4(3)	
Angles		
∠C(2)N(1)C(6)	114.6(2)	
∠N(1)C(2)C(3)/∠N(1)C(6)C(5)	123.6(2), 123.8.8(2)	
∠C(2)C(3)N(4)/∠C(6)C(5)N(4)	120.3(2), 120.6(2)	
∠C(3)N(4)C(5)	117.0(2)	
∠N(1)C(2)Cl(7)/∠N(1)C(6)Cl(10)	116.4(2), 116.5(2)	
3,6-Dichloropyridazine bond lengths		
r(N–N)	134.9(6)	135.6(7)
r[N(2)–C(3)]/*r*[N(1)–C(6)]	131.5(7), 129.9(7)	131.3(7), 129.9(7)
r[C(3)–C(4)]/*r*[C(6)–C(5)]	137.1(8), 137.5(8)	137.9(8), 138.9(7)
r[C(4)–C(5)]	135.8(8)	133.4(8)
r[C(3)–Cl(7)]/*r*[C(6)–Cl(10)]	172.6(6), 174.4(6)	173.2(6), 173.6(6)
Angles		
∠N(1)N(2)C(3)/∠N(2)N(1)C(6)	117.8(5), 118.3(4)	118.3(5), 117.5(5)
∠N(2)C(3)C(4)/∠N(1)C(6)C(5)	124.9(5), 126.3(5)	124.9(6), 125.8(5)
∠C(3)C(4)C(5)/∠C(6)C(5)C(4)	117.5(5), 115.3(5)	117.1(5), 116.3(5)
∠N(2)C(3)Cl(7)/∠N(1)C(6)Cl(10)	115.2(4), 114.6(4)	114.4(4), 114.6(4)

second molecule the most notable differences arose for *r*C(6)Cl(10), ∠C(4)C(5)C(6) and ∠C(5)C(6)N(1), distorting by −1.8(4) pm [*i.e.* a relative effect of −2.2(4) pm], −2.6(8)° and +1.8(3)°, respectively. From the intermolecular bonding, indicated in Fig. 4(*a*) by dotted lines, the observed distortions can be readily explained: the angular distortions observed for molecule 2 arise due to interactions with two neighbouring molecules, *via* a hydrogen bond between atom H(9a) of molecule 2 and N(1) of molecule 1, and between atom Cl(10a) of molecule 2 and Cl(10a) on a neighbouring molecule 2. The lengthening of the C(4)Cl(8) bond for molecule 1 can be attributed to intermolecular contact between Cl(8) and Cl(8) of a neighbouring molecule 1.

In the crystal structure of 2,6-dichloropyrazine [Fig. 4(*b*)], molecules were found to form C(H)···N bonded layers, also with close Cl···Cl contacts. Only one inter-layer contact, C(3)···C(3), appears to be present. Although deviations from the gas-phase structure greater than 3 or 4σ were found for all four ring C–N distances, all distances were found to shorten in the crystal structure by *ca.* 2 pm, which, once the average ring contraction of 1.7 pm is taken into account, can be considered to be a negligible change. In addition, ring angle changes

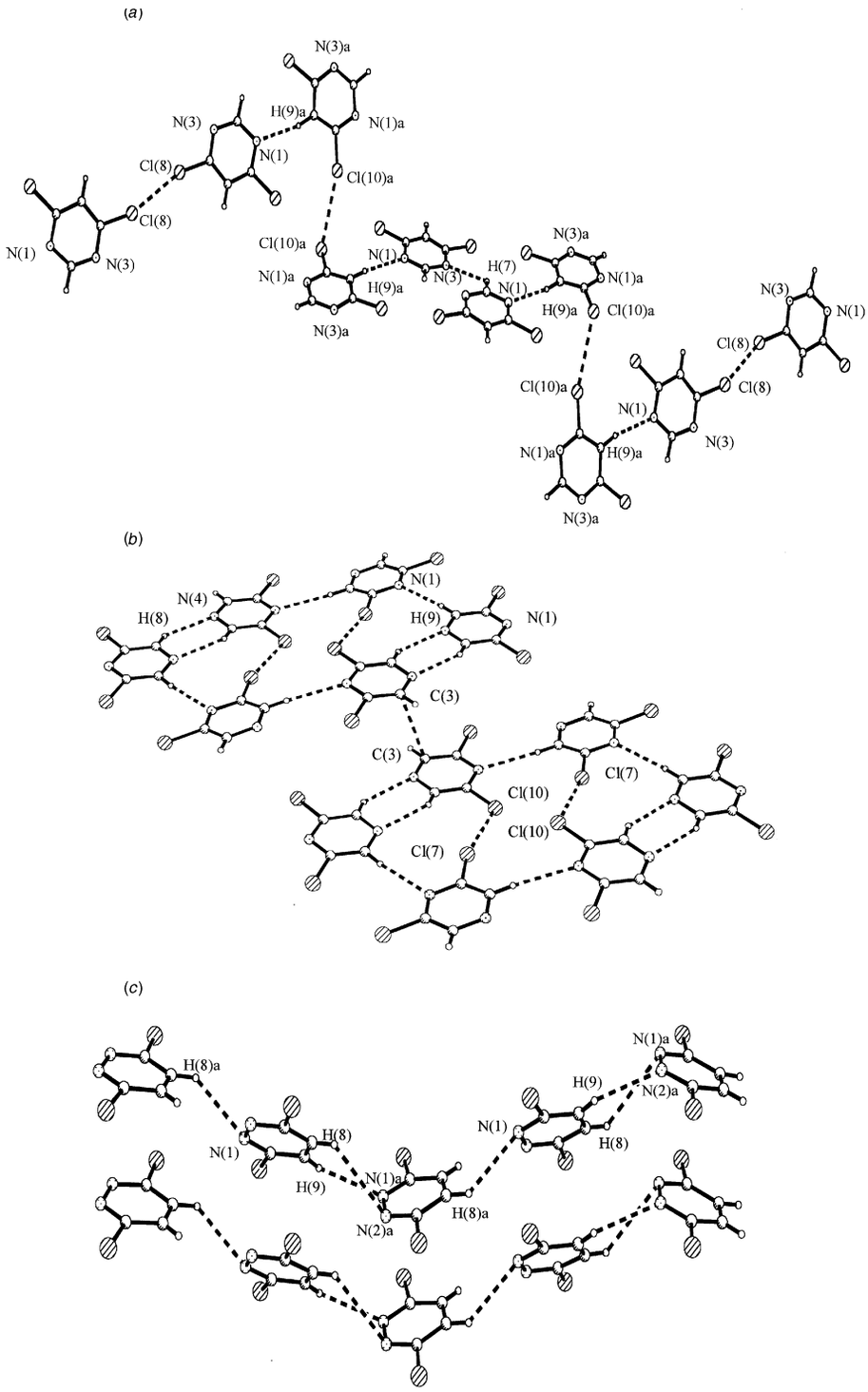

Fig. 4 (*a*) Crystal packing arrangement of 4,6-dichloropyrimidine. Molecules were found to stack in columns in alternating vertical and horizontal planes. Dotted lines indicate intermolecular bonding giving rise to significant structural distortions from the gas-phase structure. Atoms labelled 'a' after their number are in molecule 2. (*b*) Packing arrangement of 2,6-dichloropyrazine in the crystal phase. Molecules were found to pack in planes in a step-wise fashion. (*c*) Crystal packing diagram for 3,6-dichloropyridazine. Molecules were found to stack in columns in wave-like planes. Atoms labelled 'a' after their number are in molecule 2.

between the two phases average just 0.2°, which also suggests that apparent differences in structure between the two phases are due to different vibrational effects in the experimental data, and not due to crystal packing forces.

Finally, molecules in the crystal structure of 3,6-dichloropyridazine were found to stack in columns in wave-like planes, linked by three C(H) · · · N contacts per molecule [see Fig. 4(*c*)]. Taking the average ring contraction of −1.9 pm into account leaves only one bond distance which differs in the two phases by an amount greater than 3σ, namely *r*[C(4)–C(5)] in molecule 2, which is 2.8(9) pm shorter in the crystal than in the gas phase.

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References

1 S. Cradock, P. B. Liescheski, D. W. H. Rankin and H. E. Robertson, *J. Am. Chem. Soc.*, 1988, **110**, 2758.
2 S. Cradock, C. Purves and D. W. H. Rankin, *J. Mol. Struct.*, 1990, **220**, 193.
3 A. J. Blake, P. T. Brain, H. McNab, J. Miller, C. A. Morrison, S. Parsons, D. W. H. Rankin, H. E. Robertson and B. A. Smart, *J. Phys. Chem.*, 1996, **100**, 12280; P. T. Brain, C. A. Morrison, S. Parsons and D. W. H. Rankin, *J. Chem. Soc., Dalton Trans.*, 1996, 4589.
4 GAUSSIAN92, Revision F.4, M. J. Frisch, G. W. Trucks, M. Head-Gordon, P. M. W. Gill, M. W. Wong, J. B. Foresman, B. G. Johnson, H. B. Schlegel, M. A. Robb, E. S. Replogle, R. Gomperts, J. L. Andres, K. Raghavachari, J. S. Binkley, C. Gonzalez, R. L. Martin, D. J. Fox, D. J. Defrees, J. Baker, J. J. P. Stewart and J. A. Pople, Gaussian Inc., Pittsburgh, PA, 1992.
5 GAUSSIAN94, Revision C.2, M. J. Frisch, G. W. Trucks, H. B. Schlegel, P. M. W. Gill, B. G. Johnson, M. A. Robb, J. R. Cheeseman, T. Keith, G. A. Petersson, J. A. Montgomery, K. Raghavachari, M. A. Al-Laham, V. G. Zakrzewski, J. V. Ortiz, J. B. Foresman, J. Cioslowski, B. B. Stefanov, A. Nanayakkara, M. Challacombe, C. Y. Peng, P. Y. Ayala, W. Chen, M. W. Wong, J. L. Andres, E. S. Replogle, R. Gomperts, R. L. Martin, D. J. Fox, J. S. Binkley, D. J. Defrees, J. Baker, J. P. Stewart, M. Head-Gordon, C. Gonzalez and J. A. Pople, Gaussian Inc., Pittsburgh, PA, 1995.
6 J. S. Binkley, J. A. Pople and W. J. Hehre, *J. Am. Chem. Soc.*, 1980, **102**, 939.
7 M. S. Gordon, J. S. Binkley, J. A. Pople, W. J. Pietro and W. J. Hehre, *J. Am. Chem. Soc.*, 1982, **104**, 2797.
8 W. J. Pietro, M. M. Francl, W. J. Hehre, D. J. Defrees, J. A. Pople and J. S. Binkley, *J. Am. Chem. Soc.*, 1982, **104**, 5039.
9 W. J. Hehre, R. Ditchfield and J. A. Pople, *J. Chem. Phys.*, 1973, **56**, 2257.
10 P. C. Hariharan and J. A. Pople, *Theor. Chim. Acta*, 1973, **28**, 213.
11 M. S. Gordon, *Chem. Phys. Lett.*, 1980, **76**, 163.
12 A. D. McLean and G. S. Chandler, *J. Chem. Phys.*, 1980, **72**, 5639.
13 R. Krishnan, J. S. Binkley, R. Seeger and J. A. Pople, *J. Chem. Phys.*, 1980, **72**, 650.
14 ASYM40 version 3.0, update of program ASYM20. L. Hedberg and I. M. Mills, *J. Mol. Spectrosc.*, 1993, **160**, 117.
15 C. M. Huntley, G. S. Laurenson and D. W. H. Rankin, *J. Chem. Soc., Dalton Trans.*, 1980, 954.
16 S. Cradock, J. Koprowski and D. W. H. Rankin, *J. Mol. Struct.*, 1981, **77**, 113.
17 A. S. F. Boyd, G. S. Laurenson and D. W. H. Rankin, *J. Mol. Struct.*, 1981, **71**, 217.
18 A. W. Ross, M. Fink and R. Hilderbrandt, *International Tables for Crystallography*, ed. A. J. C. Wilson, Kluwer Academic Publishers, Dordrecht, The Netherlands, Boston, MA, and London, 1992, vol. C, p. 245.
19 J. Cosier and A. M. Glazer, *J. Appl. Crystallogr.*, 1986, **19**, 105.
20 G. M. Sheldrick, SHELXS-86, *Acta Crystallogr., Sect. A*, 1990, **46**, 467.
21 G. M. Sheldrick, SHELXL-93, University of Göttingen, Germany, 1993.
22 R. K. Bohn, University of Connecticut, personal communication.
23 P. B. Liescheski, D. W. H. Rankin and H. E. Robertson, *Acta Chem. Scand., Ser. A*, 1988, **42**, 338.
24 D. G. Anderson, S. Cradock, P. B. Liescheski and D. W. H. Rankin, *J. Mol. Struct.*, 1990, **216**, 181.
25 S. Cradock, P. B. Liescheski and D. W. H. Rankin, *J. Magn. Reson.*, 1991, **91**, 316.
26 A. Domenicano, *Stereochemical Applications of Gas-Phase Electron Diffraction*, eds. I. Hargittai and M. Hargittai, VCH Publishers, New York, 1988, **8**, 281.
27 A. I. Kitaigorodskii, *Advances in Structure Research by Diffraction Methods*, eds. R. Brill and R. Mason, Pergamon Press, Oxford, 1970, **3**, 173.
28 A. Domenicano and I. Hargittai, *Acta Chimica Hungarica—Models in Chemistry*, 1993, **130(3–4)**, 347.

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