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Planarity of Nitro-Substituted Phenothiazines

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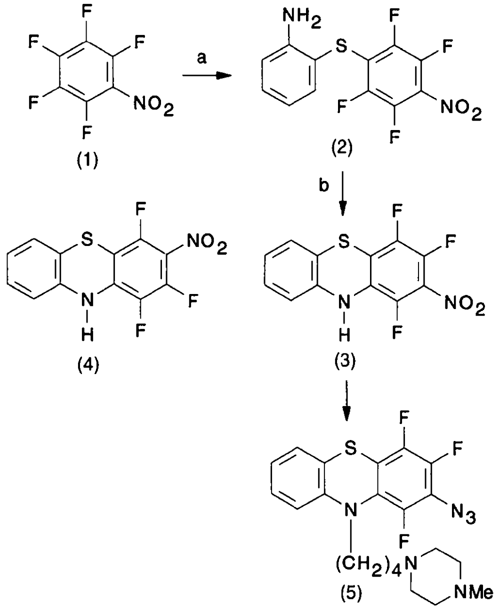
Abstract

The structures of three nitro-substituted phenothiazines [1,3,4-trifluoro-2-nitrophenothiazine, 10-(4-chlorobutyl)-1,3,4-trifluoro-2-nitrophenothiazine and 10-(4-chlorobutyl)-3-nitrophenothiazine] have been determined. The first of these red compounds forms infinite stacks in the solid state, in which donor and acceptor regions of the approximately planar molecules alternate. The molecules of the other two compounds, which have folded, or 'butterfly', conformations in the solid state, do not form stacks, presumably because the bulky chlorobutyl substituents cannot be accommodated. The very dark color of solid 3-nitrophenothiazine suggests the presence of extended molecular stacks, but crystals suitable for a structure determination could not be obtained.

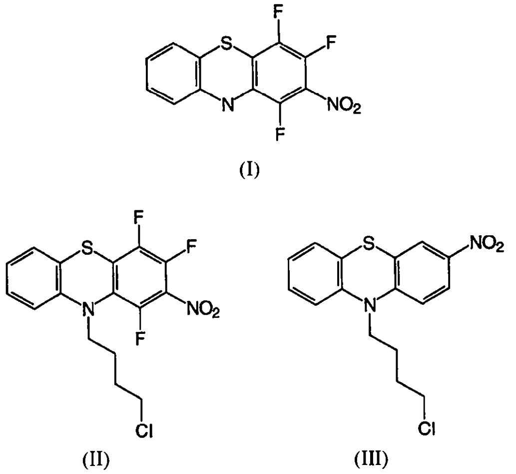
1. Introduction

A series of photoactive phenothiazines was synthesized and their binding affinities to calmodulin (CaM) were evaluated as part of an effort to study the interactions between CaM and the proteins that it regulates (Vanaman, 1983; Manalan & Klee, 1984). The synthesis (see Scheme I) of the fluorinated phenothiazine analog 2-azido-10-[4-(4-methyl-1-piperazinyl)butyl]-1,3,4-trifluorophenothiazine (5) involved an initial aromatic nucleophilic substitution reaction between pentafluoronitrobenzene (1) and 2-aminobenzenethiol to provide 2-aminophenyl 2,3,5,6-tetrafluoro-4-nitrophenyl sulfide (2). Precedent (Yakobson, Furin, Korbina & Vorozhtsov, 1967) suggested the assignment of *para*-substitution in this coupling product; that assignment was supported by ^{13}C NMR data. Heating the sulfide (2) in the presence of *N*,*N*-diisopropyl-*N*-ethylamine in 0.1 *M* *N*,*N*-dimethylformamide led efficiently to a phenothiazine derivative, but the ^{1}H and ^{13}C NMR spectra did not distinguish between the desired 2-nitro-1,3,4-trifluorophenothiazine (3) and the isomeric 3-nitro-1,2,4-trifluorophenothiazine (4), that might have arisen through a Smiles rearrangement (Truce, Kreider & Brand, 1970).

Determination of the structure of (3) (1,3,4-trifluoro-2-nitrophenothiazine, hereafter, compound I) confirmed that the desired isomer had been obtained, but revealed that the ring system, counter to expectations, was almost planar. Essentially all other neutral phenothiazines are bent along the N—S vector into a 'butterfly' conformation. Another unusual property of (I) is its color: solutions and crystals are bright red. Structures of the related molecules 10-(4-chlorobutyl)-1,3,4-trifluoro-2-nitrophenothiazine (hereafter, compound II) and 10-(4-chlorobutyl)-3-nitrophenothiazine (hereafter, compound III) were then determined to determine



Scheme I.



Scheme II.

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whether the unexpected geometry was characteristic of the substitution pattern or an accident of crystal packing.

2. Experimental

The three crystals structures were solved with the program package *SHELXTL/PC* (Sheldrick, 1990) and refined with *SHELXL*93 (Sheldrick, 1993). H atoms were located in calculated positions and refined isotropically; all C—H distances were in the range 0.86–1.08 Å with e.s.d.'s of *ca* 0.03 Å. Crystallographic data and the details of the structure determinations are given in Table 1, atomic coordinates and isotropic *U* values in Tables 2–4, and bond lengths and angles in Table 5. The molecular structures and the atom-numbering scheme are displayed in Figs. 1–3; crystal packing is displayed in Figs. 4–6.*

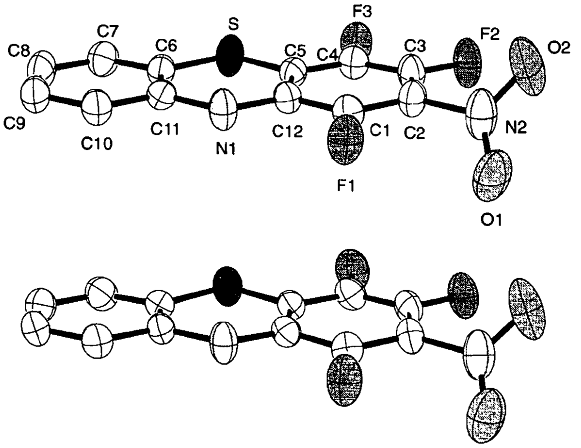

Fig. 1. Perspective drawing of the molecular structure of (I). Molecule *A* is above molecule *B*. The shapes of the ellipsoids of the non-H atoms here and in Figs. 2 and 3 correspond to 50% probability contours of atomic displacement.

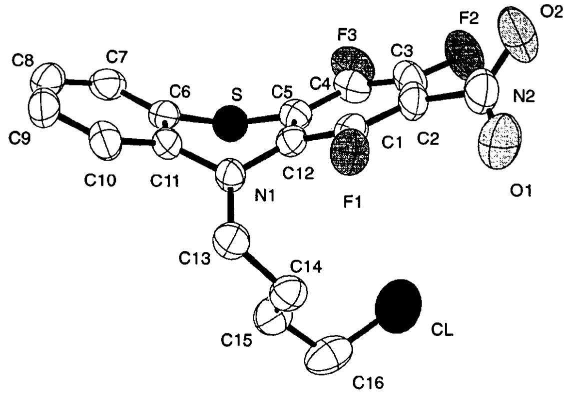

Fig. 2. Perspective drawing of the molecular structure of (II).

A search of the July 1993 version of the Cambridge Structural Database (Allen, Kennard & Taylor, 1983; hereafter, the CSD) for the phenothiazine ring structure ($C_{12}NS$; no other bond to the S atom) included the criteria RFAC 0.01–0.07 and SIGF 1-3 (average e.s.d. for a C—C bond 0.001–0.030). Structures with charges marked were rejected, as was one structure with a bridge between the N atom and one of the rings. The 44 'hits' yielded 55 phenothiazine fragments. The refcodes and dihedral angles have been deposited.*

3. Results

Comparison of Figs. 1–3 shows that a planar phenothiazine ring system is found in (I), but not in the other two compounds. The dihedral angle between the two C_6NS planes in (I) is 3.3 (1) and 2.4 (1)° for the two independent molecules, but 40.6 (1)° in (II) and 25.2 (1)° in (III). The histogrammic representation (Fig. 7) of the corresponding values derived from the CSD shows that the value found for (II) of 41° is typical for phenothiazines. The value for (III) of 25° is close to the edge of the main part of the distribution, but is not remarkable. The very small values of the dihedral angles for (I) are, however, unusual, especially when the six structures having dihedral angles $< 10^\circ$ are examined more carefully. All six structures (seven fragments) are solid-state compounds composed of two different ions or molecules. Four of the structures (five fragments) are described in the orignal articles (although not in the CSD) as containing the radical cation of phenothiazine (Kozawa & Uchida, 1990; Von Dreele & Harris, 1983; Singhabhandhu, Robinson, Fang & Geiger, 1975). The other two fragments occur in the 1:1 and 2:1 π-molecular complexes of phenothiazine with pyromellitic dianhydride (Anthonj, Karl, Robertson & Stezowski, 1980; Brierly, Barton, Robertson, Anthonj & Karl, 1985). Compound (I) appears to be the only simple uncomplexed phenothiazine in which the characteristic $C_{12}NS$ fragment is almost planar.

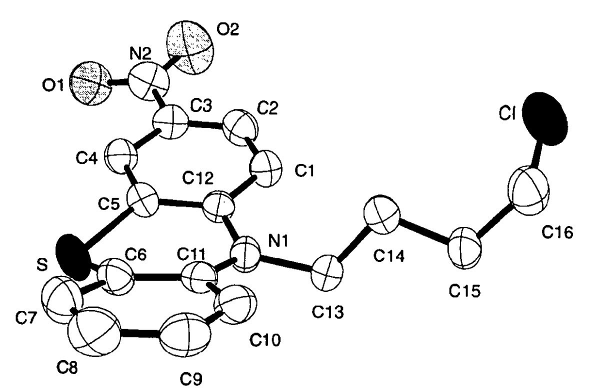

Fig. 3. Perspective drawing of the molecular structure of (III).

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* Lists of anisotropic displacement parameters, bond lengths and angles involving H atoms, structure factors, and refcodes and dihedral angles have been deposited with the IUCr (Reference: CR0504). Copies may be obtained through The Managing Editor, International Union of Crystallography, 5 Abbey Square, Chester CH1 2HU, England.

* See deposition footnote.

Table 1. *Experimental details*

	(I)	(II)	(III)
Crystal data			
Chemical formula	$C_{12}H_5F_3N_2O_2S$	$C_{16}H_{12}ClF_3N_2O_2S$	$C_{16}H_{15}ClN_2O_2S$
Chemical formula weight	298.24	388.80	334.82
Cell setting	Triclinic	Monoclinic	Monoclinic
Space group	$P\bar{1}$	$P2_1/c$	$P2_1/c$
a (Å)	6.9087 (7)	6.0144 (5)	9.3191 (5)
b (Å)	11.9009 (4)	22.4675 (16)	18.4382 (11)
c (Å)	14.3626 (12)	12.0544 (5)	9.2060 (9)
α (°)	85.715 (4)		
β (°)	78.994 (9)	91.224 (5)	104.004 (6)
γ (°)	82.860 (6)		
V (Å^3)	1148.6 (2)	1628.5 (2)	1534.8 (2)
Z	4	4	4
D_x (Mg m^{-3})	1.725	1.586	1.449
Radiation type	Mo $K\alpha$	Mo $K\alpha$	Mo $K\alpha$
Wavelength (Å)	0.71073	0.71073	0.71073
No. of reflections for cell parameters	22	22	22
θ range (°)	10.5–12.8	12.1–13.3	10.9–12.8
μ (mm^{-1})	0.310	0.399	0.384
Temperature (K)	295 (2)	296 (1)	295 (2)
Crystal form	Needles elongated along **a**. The major faces are $\{011\}$. Other faces observed are $\{001\}$, $\{01\bar{1}\}$, $\{\bar{1}01\}$ and $\{\bar{1}10\}$. The crystals are sometimes twinned across $\{011\}$ planes	Needles. Long axis is **a**. Major faces are $\{011\}$	Laths elongated along **c**; short dimension is **a**. Major faces are $\{100\}$, $\{010\}$ and $\{011\}$
Crystal size (mm)	0.58 × 0.15 × 0.08	0.52 × 0.30 × 0.22	0.58 × 0.25 × 0.11
Crystal color	Ruby red	Orange–red	Bright red
Crystallization conditions	From chloroform solutions at room temperature	From isopropanol solutions at room temperature	From *ca* 8:1 hexane:ethylacetate solutions at 473 K
M.p. (K)	445–446.5	345.5–346.5	360–361.5
Data collection			
Diffractometer	Enraf–Nonius CAD-4	Enraf–Nonius CAD-4	Enraf–Nonius CAD-4
Monochromator	Graphite	Graphite	Graphite
$(\sin\theta/\lambda)_{max}$ (Å^{-1})	0.65	0.65	0.65
Data collection method	$\omega/2\theta$ scans	$\omega/2\theta$ scans	$\omega/2\theta$ scans
Maximum count time (s)	45	100	100
Absorption correction	None	Based on four Ψ scans (Flack, 1977)	None
T_{min}	–	0.88	–
T_{max}	–	0.94	–
No. of measured reflections	5281	3728	3503
No. of independent reflections	5281	3728	3503
No. of observed reflections	2897	2280	1667
Criterion for observed reflections	$I > 2\sigma(I)$	$I > 2\sigma(I)$	$I > 2\sigma(I)$
θ_{max} (°)	27.59	27.50	27.49
Range of h, k, l	$0 \rightarrow h \rightarrow 9$ $-15 \rightarrow k \rightarrow 15$ $-18 \rightarrow l \rightarrow 18$	$0 \rightarrow h \rightarrow 7$ $0 \rightarrow k \rightarrow 29$ $-15 \rightarrow l \rightarrow 15$	$-12 \rightarrow h \rightarrow 11$ $0 \rightarrow k \rightarrow 23$ $0 \rightarrow l \rightarrow 11$
No. of standard reflections	3	3	3
Frequency of standard reflections (min)	60	60	60
Intensity decay (%)	<2	<1	<1
Refinement			
Refinement on	F^2	F^2	F^2
R	0.051	0.038	0.042
wR	0.116	0.088	0.101
S	1.14	1.10	1.16
No. of reflections used in refinement	5279*	3728	3503
No. of parameters used	401	274	259
H-atom treatment	All H-atom parameters refined	All H-atom parameters refined	All H-atom parameters refined
Weighting scheme	$w = 1/[\sigma^2(F_o^2) + (0.0557P)^2 + 0.1233P]$, where $P = (F_o^2 + 2F_c^2)/3$	$w = 1/[\sigma^2(F_o^2) + (0.0428P)^2 + 0.5611P]$, where $P = (F_o^2 + 2F_c^2)/3$	$w = 1/[\sigma^2(F_o^2) + (0.0611P)^2 + 0.2296P]$, where $P = (F_o^2 + 2F_c^2)/3$
$(\Delta/\sigma)_{max}$	0.01	0.09	−0.08
$\Delta\rho_{max}$ (e Å^{-3})	0.27	0.23	0.37
$\Delta\rho_{min}$ (e Å^{-3})	−0.27	−0.30	−0.25
Extinction method	None	None	None
Source of atomic scattering factors	*International Tables for Crystallography* (1992, Vol. C, Tables 4.2.6.8 and 6.1.1.4)	*International Tables for Crystallography* (1992, Vol. C, Tables 4.2.6.8 and 6.1.1.4)	*International Tables for Crystallography* (1992, Vol. C, Tables 4.2.6.8 and 6.1.1.4)

* Two very intense reflections were deleted because of a problem with the attenuator.

Table 2. *Fractional atomic coordinates and equivalent isotropic displacement parameters (Å²) for (I)*

$U_{\rm eq} = (1/3)\Sigma_i\Sigma_j U_{ij} a_i^* a_j^* \mathbf{a}_i.\mathbf{a}_j.$

	x	y	z	$U_{\rm eq}$
S*A*	0.3391 (2)	0.62144 (7)	0.34871 (6)	0.0544 (3)
F1*A*	0.1829 (3)	0.7227 (2)	0.69712 (12)	0.0547 (5)
F2*A*	0.3085 (4)	1.0133 (2)	0.45911 (14)	0.0672 (7)
F3*A*	0.3663 (3)	0.8597 (2)	0.32747 (12)	0.0588 (6)
O1*A*	0.3133 (5)	0.9347 (2)	0.7154 (2)	0.0742 (9)
O2*A*	0.0974 (5)	1.0369 (2)	0.6464 (2)	0.0880 (11)
N1*A*	0.2298 (5)	0.5639 (2)	0.5675 (2)	0.0442 (7)
N2*A*	0.2157 (5)	0.9530 (2)	0.6529 (2)	0.0565 (9)
C1*A*	0.2288 (5)	0.7567 (3)	0.6053 (2)	0.0385 (7)
C2*A*	0.2422 (5)	0.8705 (3)	0.5808 (2)	0.0417 (8)
C3*A*	0.2865 (5)	0.9044 (2)	0.4863 (2)	0.0458 (8)
C4*A*	0.3170 (5)	0.8254 (3)	0.4195 (2)	0.0409 (8)
C5*A*	0.2990 (5)	0.7118 (2)	0.4423 (2)	0.0360 (7)
C6*A*	0.2889 (5)	0.4907 (3)	0.4095 (2)	0.0412 (7)
C7*A*	0.3016 (6)	0.3996 (3)	0.3528 (3)	0.0508 (9)
C8*A*	0.2678 (6)	0.2931 (3)	0.3932 (3)	0.0547 (10)
C9*A*	0.2205 (6)	0.2781 (3)	0.4907 (3)	0.0527 (9)
C10*A*	0.2069 (5)	0.3687 (3)	0.5473 (3)	0.0454 (8)
C11*A*	0.2420 (5)	0.4761 (3)	0.5075 (2)	0.0382 (7)
C12*A*	0.2528 (5)	0.6761 (2)	0.5384 (2)	0.0357 (7)
S*B*	0.2024 (2)	0.06280 (7)	0.13603 (6)	0.0525 (3)
F1*B*	0.2548 (3)	0.2128 (2)	−0.20964 (12)	0.0564 (6)
F2*B*	0.1906 (3)	0.4731 (2)	0.03082 (14)	0.0631 (6)
F3*B*	0.1825 (4)	0.2997 (2)	0.15972 (13)	0.0631 (6)
O1*B*	0.1192 (5)	0.4391 (2)	−0.2244 (2)	0.0742 (9)
O2*B*	0.3329 (5)	0.5122 (2)	−0.1610 (2)	0.0868 (10)
N1*B*	0.2608 (5)	0.0361 (2)	−0.0835 (2)	0.0455 (7)
N2*B*	0.2230 (5)	0.4399 (2)	−0.1648 (2)	0.0569 (9)
C1*B*	0.2347 (5)	0.2354 (3)	−0.1182 (2)	0.0388 (7)
C2*B*	0.2213 (5)	0.3463 (2)	−0.0924 (2)	0.0408 (8)
C3*B*	0.2060 (5)	0.3672 (3)	0.0018 (2)	0.0429 (8)
C4*B*	0.2004 (5)	0.2781 (3)	0.0676 (2)	0.0419 (8)
C5*B*	0.2142 (5)	0.1669 (2)	0.0434 (2)	0.0371 (7)
C6*B*	0.2349 (5)	−0.0627 (3)	0.0727 (2)	0.0405 (7)
C7*B*	0.2345 (6)	−0.1639 (3)	0.1273 (3)	0.0513 (9)
C8*B*	0.2631 (6)	−0.2664 (3)	0.0850 (3)	0.0554 (10)
C9*B*	0.2937 (6)	−0.2677 (3)	−0.0121 (3)	0.0506 (9)
C10*B*	0.2925 (5)	−0.1678 (3)	−0.0666 (3)	0.0441 (8)
C11*B*	0.2625 (5)	−0.0637 (2)	−0.0254 (2)	0.0387 (7)
C12*B*	0.2367 (5)	0.1438 (2)	−0.0523 (2)	0.0365 (7)

Table 3. *Fractional atomic coordinates and equivalent isotropic displacement parameters (Å²) for (II)*

$U_{\rm eq} = (1/3)\Sigma_i\Sigma_j U_{ij} a_i^* a_j^* \mathbf{a}_i.\mathbf{a}_j.$

	x	y	z	$U_{\rm eq}$
Cl	0.3650 (2)	0.23091 (5)	0.88128 (8)	0.1006 (3)
S	0.39141 (9)	0.41528 (3)	0.62282 (5)	0.0499 (2)
F1	−0.3099 (2)	0.34785 (6)	0.81093 (10)	0.0525 (3)
F2	0.2350 (3)	0.44634 (8)	1.02936 (12)	0.0835 (5)
F3	0.4805 (2)	0.46133 (7)	0.84907 (13)	0.0710 (4)
O1	−0.2902 (4)	0.34540 (11)	1.0288 (2)	0.0899 (7)
O2	−0.1946 (4)	0.43333 (12)	1.0808 (2)	0.0958 (8)
N1	−0.0364 (3)	0.35005 (8)	0.62634 (14)	0.0413 (4)
N2	−0.1862 (4)	0.39122 (12)	1.0179 (2)	0.0623 (6)
C1	−0.1090 (3)	0.37323 (10)	0.8206 (2)	0.0416 (5)
C2	−0.0416 (4)	0.39625 (11)	0.9226 (2)	0.0487 (6)
C3	0.1591 (4)	0.42577 (12)	0.9314 (2)	0.0554 (6)
C4	0.2855 (4)	0.43229 (10)	0.8395 (2)	0.0504 (6)
C5	0.2220 (3)	0.40840 (10)	0.7379 (2)	0.0413 (5)
C6	0.1799 (4)	0.41866 (9)	0.5187 (2)	0.0415 (5)
C7	0.2098 (5)	0.45313 (11)	0.4247 (2)	0.0536 (6)
C8	0.0519 (5)	0.45226 (12)	0.3397 (2)	0.0599 (7)
C9	−0.1346 (5)	0.41794 (13)	0.3496 (2)	0.0572 (7)
C10	−0.1692 (4)	0.38400 (11)	0.4436 (2)	0.0480 (5)
C11	−0.0091 (3)	0.38395 (9)	0.5292 (2)	0.0387 (5)
C12	0.0230 (3)	0.37633 (9)	0.7278 (2)	0.0371 (4)
C13	−0.1483 (4)	0.29168 (11)	0.6216 (2)	0.0469 (5)
C14	−0.0381 (4)	0.24682 (11)	0.6992 (2)	0.0479 (5)
C15	0.1988 (5)	0.23199 (13)	0.6698 (2)	0.0596 (7)
C16	0.3183 (6)	0.19329 (14)	0.7539 (3)	0.0737 (9)

Table 4. *Fractional atomic coordinates and equivalent isotropic displacement parameters (Å²) for (III)*

$U_{\rm eq} = (1/3)\Sigma_i\Sigma_j U_{ij} a_i^* a_j^* \mathbf{a}_i.\mathbf{a}_j.$

	x	y	z	$U_{\rm eq}$
Cl	0.24359 (12)	0.22030 (4)	0.61198 (11)	0.0724 (3)
S	0.00838 (10)	0.63990 (4)	0.21434 (10)	0.0534 (3)
O1	−0.4290 (3)	0.5021 (2)	−0.1344 (3)	0.0722 (7)
O2	−0.4023 (3)	0.3884 (2)	−0.0838 (4)	0.0990 (11)
N1	0.1752 (3)	0.50527 (12)	0.3573 (3)	0.0397 (6)
N2	−0.3596 (3)	0.4515 (2)	−0.0657 (3)	0.0596 (8)
C1	−0.0034 (4)	0.4213 (2)	0.2113 (4)	0.0452 (8)
C2	−0.1345 (4)	0.4084 (2)	0.1062 (4)	0.0483 (8)
C3	−0.2230 (3)	0.4654 (2)	0.0438 (3)	0.0454 (8)
C4	−0.1816 (4)	0.5362 (2)	0.0837 (3)	0.0442 (8)
C5	−0.0500 (3)	0.54940 (15)	0.1855 (3)	0.0383 (7)
C6	0.1253 (3)	0.6333 (2)	0.3941 (3)	0.0429 (7)
C7	0.1487 (4)	0.6959 (2)	0.4818 (4)	0.0555 (9)
C8	0.2543 (4)	0.6971 (2)	0.6160 (4)	0.0608 (10)
C9	0.3322 (4)	0.6349 (2)	0.6643 (4)	0.0535 (9)
C10	0.3045 (3)	0.5711 (2)	0.5822 (4)	0.0472 (8)
C11	0.2009 (3)	0.56896 (15)	0.4445 (3)	0.0372 (7)
C12	0.0420 (3)	0.49211 (15)	0.2541 (3)	0.0375 (7)
C13	0.2811 (4)	0.4448 (2)	0.3989 (4)	0.0432 (8)
C14	0.2560 (4)	0.3946 (2)	0.5211 (4)	0.0495 (8)
C15	0.3883 (4)	0.3450 (2)	0.5756 (5)	0.0543 (9)
C16	0.3693 (5)	0.2918 (2)	0.6933 (5)	0.0647 (11)

Table 5. *Bond lengths (Å) and angles (°)*

	(I)		(II)	(III)
S—C5	1.744 (3)	1.746 (3)	1.745 (2)	1.755 (3)
S—C6	1.766 (3)	1.774 (3)	1.769 (2)	1.752 (3)
F1—C1	1.340 (3)	1.337 (3)	1.339 (2)	
F2—C3	1.344 (3)	1.342 (3)	1.339 (3)	
F3—C4	1.346 (3)	1.347 (3)	1.345 (3)	
O1—N2	1.214 (4)	1.218 (4)	1.213 (3)	1.221 (4)
O2—N2	1.219 (4)	1.227 (4)	1.214 (3)	1.228 (4)
N1—C11	1.388 (4)	1.399 (4)	1.409 (3)	1.410 (3)
N1—C12	1.387 (4)	1.370 (4)	1.398 (3)	1.389 (4)
N2—C2	1.451 (4)	1.465 (4)	1.460 (3)	
N2—C3				1.443 (4)
C1—C2	1.383 (4)	1.386 (4)	1.387 (3)	1.383 (4)
C1—C12	1.381 (4)	1.389 (4)	1.387 (3)	1.399 (4)
C2—C3	1.375 (4)	1.375 (4)	1.379 (3)	1.373 (4)
C3—C4	1.362 (4)	1.366 (4)	1.365 (3)	1.385 (4)
C4—C5	1.383 (4)	1.380 (4)	1.383 (3)	1.373 (4)
C5—C12	1.402 (4)	1.398 (4)	1.400 (3)	1.410 (4)
C6—C7	1.389 (4)	1.388 (4)	1.388 (3)	1.394 (4)
C6—C11	1.386 (4)	1.387 (4)	1.386 (3)	1.401 (4)
C7—C8	1.382 (5)	1.378 (5)	1.382 (4)	1.381 (5)
C8—C9	1.379 (5)	1.371 (5)	1.369 (4)	1.373 (5)
C9—C10	1.381 (5)	1.374 (5)	1.386 (3)	1.388 (5)
C10—C11	1.392 (4)	1.387 (4)	1.397 (3)	1.396 (4)
N1—C13			1.475 (3)	1.477 (4)
C13—C14			1.518 (3)	1.518 (5)
C14—C15			1.513 (3)	1.519 (5)
C15—C16			1.507 (4)	1.503 (5)
C16—Cl			1.770 (4)	1.802 (4)
C5—S—C6	101.52 (15)	101.35 (14)	98.30 (10)	100.16 (14)
C11—N1—C12	125.4 (3)	125.4 (3)	117.8 (2)	122.4 (2)
O1—N2—O2	124.1 (3)	125.3 (3)	124.5 (2)	122.7 (3)
O1—N2—C2	118.1 (3)	118.1 (3)	117.9 (2)	
O2—N2—C2	117.8 (3)	116.6 (3)	117.7 (3)	
O1—N2—C3				119.5 (3)
O2—N2—C3				117.7 (3)
F1—C1—C2	119.4 (3)	120.2 (3)	118.8 (2)	
F1—C1—C12	118.0 (3)	117.5 (3)	118.9 (2)	
C2—C1—C12	122.6 (3)	122.2 (3)	122.3 (2)	120.9 (3)
C1—C2—C3	118.8 (3)	119.2 (3)	119.1 (2)	120.0 (3)
C1—C2—N2	121.2 (3)	120.1 (3)	120.1 (2)	
C3—C2—N2	120.0 (3)	120.7 (3)	120.7 (2)	
F2—C3—C2	121.0 (3)	121.6 (3)	121.0 (2)	
F2—C3—C4	119.6 (3)	119.3 (3)	119.6 (2)	
N2—C3—C2				119.7 (3)
N2—C3—C4				119.7 (3)

Table 5 (*cont.*)

	(I)		(II)	(III)
C2—C3—C4	119.3 (3)	119.1 (3)	119.3 (2)	120.6 (3)
F3—C4—C3	118.5 (3)	118.5 (3)	118.8 (2)	
F3—C4—C5	118.7 (3)	118.7 (3)	119.2 (2)	
C3—C4—C5	122.8 (3)	122.7 (3)	122.0 (2)	119.6 (3)
C4—C5—C12	118.5 (3)	119.0 (3)	119.7 (2)	121.2 (3)
S—C5—C4	117.3 (2)	117.1 (2)	121.0 (2)	117.7 (2)
S—C5—C12	124.2 (2)	123.9 (2)	119.3 (2)	120.8 (2)
C7—C6—C11	120.4 (3)	120.1 (3)	120.6 (2)	120.9 (3)
S—C6—C7	115.8 (3)	116.1 (3)	120.0 (2)	117.7 (2)
S—C6—C11	123.8 (2)	123.9 (2)	119.3 (2)	121.3 (2)
C6—C7—C8	120.5 (3)	120.7 (3)	119.9 (3)	120.6 (3)
C7—C8—C9	119.4 (3)	119.4 (3)	119.7 (2)	118.9 (3)
C8—C9—C10	120.3 (3)	120.2 (3)	121.2 (3)	121.2 (3)
C9—C10—C11	120.9 (3)	121.3 (3)	119.5 (2)	121.0 (3)
N1—C11—C6	122.8 (3)	122.2 (3)	119.4 (2)	121.0 (2)
N1—C11—C10	118.7 (3)	119.5 (3)	121.6 (2)	121.7 (3)
C6—C11—C10	118.5 (3)	118.3 (3)	119.1 (2)	117.3 (3)
N1—C12—C1	119.8 (3)	119.1 (3)	123.0 (2)	121.0 (3)
N1—C12—C5	122.2 (3)	123.1 (3)	119.7 (2)	121.4 (2)
C1—C12—C5	118.0 (3)	117.8 (3)	117.3 (2)	117.6 (3)
C12—N1—C13			121.2 (2)	118.4 (2)
C11—N1—C13			120.6 (2)	118.0 (2)
N1—C13—C14			111.9 (2)	116.1 (3)
C13—C14—C15			113.7 (2)	110.7 (3)
C14—C15—C16			114.1 (2)	113.7 (3)
C15—C16—C1			111.9 (2)	110.9 (3)

Bond lengths and angles are normal (Allen, Kennard, Watson, Brammer, Orpen & Taylor, 1987). The torsion angles describing the rotations of the nitro groups around the C—N bond from coplanarity with the C_6 ring are 53 and 46° in the two molecules of (I), 38° in (II) and 9° in (III) (all e.s.d.'s *ca* 1°).

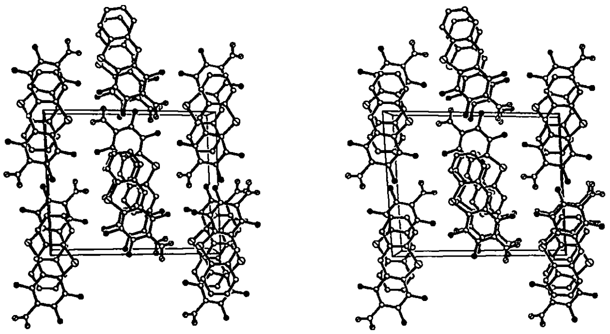

Fig. 4. Stereoscopic view of the unit cell of (I). Here and in Figs. 5 and 6 a few extra molecules have been included to better illustrate the interactions in the direction perpendicular to the plane of the drawing. The *c* axis points to the left, the *b* axis points upwards and the *a* axis points out of the plane of the paper.

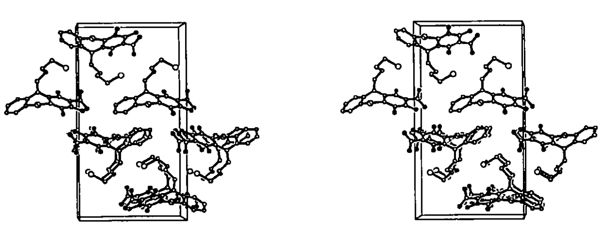

Fig. 5. Stereoscopic view of the unit cell of (II). The *c* axis points to the right, the *b* axis points downwards and the *a* axis points out of the plane of the paper.

4. Discussion

Phenothiazine is a known electron donor in π-donor–acceptor complexes with ionic and nonionic ground states (Herbstein, 1971). The folding of the molecule along the N—S vector is small in these compounds; the molecule is approximately planar. The addition of the electron-accepting nitro group to the phenothiazine fragment opens up the possibility of phenothiazine forming complexes with itself. A number of resonance structures can be drawn which have a formal positive charge localized on the N or S atom and a formal negative charge on the NO_2 group.

The structural evidence suggests that molecules of (I), which contain both an electron donor and acceptor, could be regarded as self-complexing (*cf.* Herbstein, 1971). Within the stacks the two ends of the fused-ring system alternate (see Figs. 4 and 8). The angle of the best molecular plane with respect to the *a* axis is 13.49 (4)° for molecule *A* and 10.26 (4)° for molecule *B*. The distances between the planes of adjacent molecules are 3.34 (2) and 3.44 (2) Å for molecule *A* (inversion centers at 0,1/2,1/2 and 1/2,1/2,1/2) and 3.40 (1) and 3.47 (1) Å

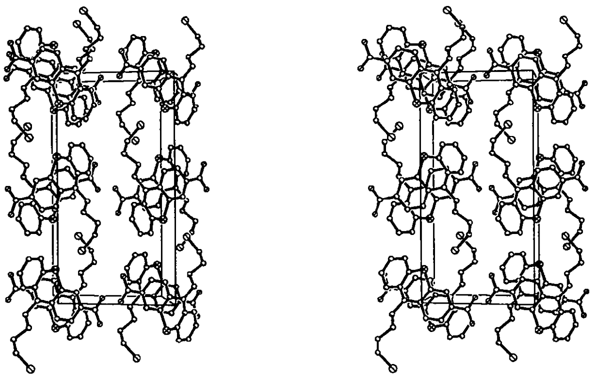

Fig. 6. Stereoscopic view of the unit cell of (III). The *a* axis points to the left, the *b* axis points downwards and the *c* axis points out of the plane of the paper.

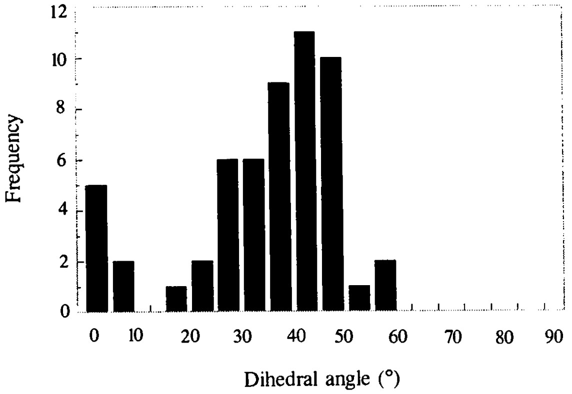

Fig. 7. Histogram showing the distribution of dihedral angles between C_6NS planes in 55 phenothiazine fragments. Bins are 5° wide; the first bin includes structures with angles between 0 and 5°.

for molecule *B* (inversion centers at 0,0,0 and 1/2,0,0). These distances are a little longer than the distances in many solid-state complexes and thus indicate only weak charge-transfer interactions (Herbstein, 1971).

The crystal morphology provides further evidence of stacking interactions. Crystals of (I) are elongated parallel to the stacking *a* axis, but are thin in the direction of the normals to the large {011} faces. The crystals cleave easily to produce new {011} faces, across which twinning seems to be common. Finally, the melting point (see Table 1) is 100 K higher for (I) than for (II), even though an H atom in the former is replaced by a (much heavier) C_4H_8Cl group in the latter. On the other hand, it could be argued that the higher melting point of (I) is, at least in part, simply a reflection of its greater density (see Table 1).

The two independent molecules of (I) are approximately planar (r.m.s. deviations from the 18-atom planes of 0.040 and 0.042 Å for molecules *A* and *B*, respectively). A view of the crystal packing (see Fig. 8) suggests that the molecules might be slightly bowed; the deviations from the least-squares planes imply, however, that molecule *A* is bowed, but *B* is twisted (see Fig. 9). The atomic displacement ellipsoids (see Fig. 1) seem to rule out the possibility of the planar geometry resulting from disorder of two more folded molecules. Although the ellipsoids for the S and N1 atoms are larger than those of the adjacent C atoms, they are no more elongated than the ellipsoid for the S atom in (III) (see Fig. 3).

Replacement of the H attached to N1 with the bulky C_4H_8Cl group breaks up the molecular stacking. The folded phenothiazine rings in (II) interact in layers centered around $y = 0$ and $y = 1/2$ and the chlorobutyl groups interact in layers centered around $y = 1/4$ and $y = 3/4$. The molecules in (III) (see Fig. 6) appear to interact in pairs.

The red color of all three compounds, and of seven other members of a series of neutral phenothiazine derivatives having a nitro substituent attached to C2 or C3, appears to be typical of nitrophenothiazines. All ten become colorless if the nitro group is reduced to an amino group (Golinski, DeLaLuz, Floresca, Delcamp, Vanaman & Watt, 1995). The crystal structures of the two chlorobutyl phenothiazine derivatives (II and III), which are both significantly folded along the N–S vector, show that a red color does not imply coplanarity of the fused rings.

Crystals of 3-nitrophenothiazine appear black, but are seen to be dark red when very thin samples are viewed under a microscope. Attempts to determine whether these crystals also contain molecular stacks were thwarted when repeated recrystallization attempts produced nothing but aggregates of microcrystals. If the crystals do contain stacks, then neither the position (2- *versus* 3-) of the nitro substituent nor the replacement of F with H atoms affects the crystal packing.

The only other nitro-substituted phenothiazine derivative that we could find in the literature is the oxidation product 2-chloro-7-nitro-10-methylphenothiazine 5-oxide (Jovanovic, de Meester, Biehl & Chu, 1986). This molecule is slightly folded (dihedral angle 15.5°) and appears to pack as dimers. The O atom attached to the S atom is very much out of the 'plane' of the rest of the molecule and so probably hinders the formation of stacks. Another interesting comparison compound is 1,4,6,9-tetraazathianthrene, $C_8H_4N_4S_2$ (Lynch, Simonsen, Davis, Martin, Musmar, Lam & Smith, 1994), which is one of the few known planar thianthrenes (same ring system as phenothiazine except that the N atom is replaced by a second S atom). Tetraazathianthrene molecules form stacks generated by the *a* translation (3.89 Å).

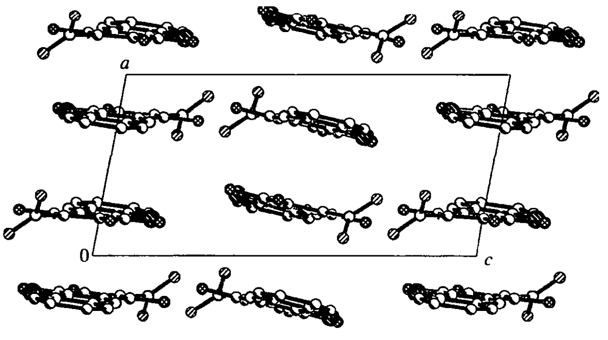

Fig. 8. Projection of part of the structure of (I) along the *b* axis. The *a* axis points upwards and the *c* axis points towards the right. Molecules *A* in the same stack are related by translations along **a** and by inversion centers at $y = z = 1/2$; the inversion centers relating molecules in the *B* stack are at $y = z = 0$.

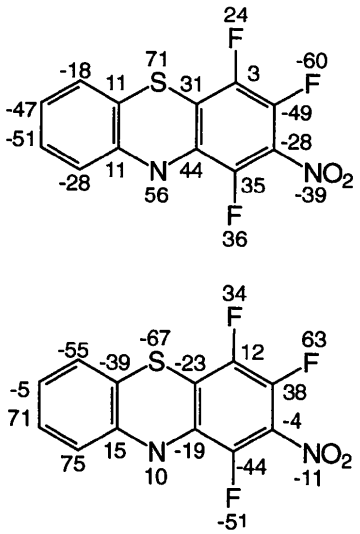

Fig. 9. Diagram showing the deviations (in Å × 10^3) of the atoms of (I) from the best molecular planes. Molecule *A* is above molecule *B*. Standard deviations are 0.003 Å for C atoms, 0.002 Å for N atoms and 0.001 Å for S atoms.

We conclude that the stacking interactions in nitrophenothiazines are weak. In the absence of bulky substituents or out-of-plane substituents infinite stacks may be formed in which donor and acceptor regions (or bond polarities) alternate. Whatever charge-transfer interactions stacking may provide, it almost certainly leads to greater packing efficiency and thus a lower crystal energy. The tendency of these molecules to stack is, however, easily overwhelmed by other types of interactions.

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