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CRYSTAL ENGINEERING THROUGH NON-BONDED CONTACTS TO SULPHUR. STRUCTURE AND SOLID STATE PHOTOREACTIVITY OF 4-(4'-CHLORO)-PHENYL-Δ-4-THIAZOLENE-2-THIONE.

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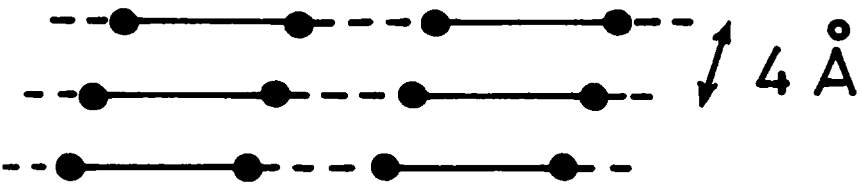
Abstract - Weak but directionally specific *interstack* S....S and S....Cl contacts may be used to engineer the 4 Å - short axis β-structure for a planar sulphur heterocycle. A representative compound is the title thione **2**. Crystals of **2** are monoclinic, $P2_1/n$, Z=8, a=17.327(4), b=3.950(2), c=27.877(6) Å, β=93.88(2)°; R=0.050, R_w=0.044 on 783 non-zero reflections. Molecules related by translation along [010] are within photoreactive distance and the β-structure leads to the rapid formation on UV irradiation of a fused tricyclic mirror symmetry cyclobutane **3**. This dimer is very unstable and collapses thermally to the novel ten-membered diolefin **4**. The β-packing mode is adopted by several other related sulphur heterocycles.

Introduction

While coining the term 'crystal engineering', Schmidt correctly pointed out that the systematic development of organic solid state chemistry would be difficult if not impossible until the intermolecular forces responsible for crystal stabilisation were understood.[1] Subsequent events have shown his early prognosis to be remarkably accurate. The topochemical principle has been repeatedly confirmed and there has been a natural shift in emphasis from obtaining crystal structures of molecular solids to understanding the forces which control and stabilise such structures. So, crystal engineering which attempts a predictive design of solids has become, in effect, a study of weak intermolecular interactions and incorporates organic chemistry, crystallography and chemical physics in a synergistic combination.[2]

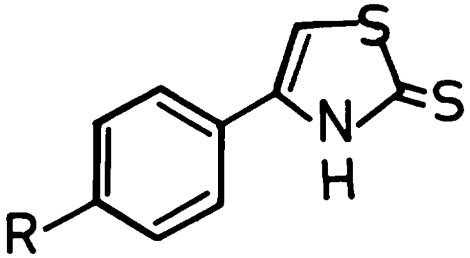
Planar aromatic molecules are convenient targets in crystal engineering since variations in conformation and stereochemistry are usually absent. When such molecules are translated along a crystallographic short axis, two broad situations arise with the axis between 3.7 and 4.2 Å (β-structure) or greater than 4.7 Å (non-β structure). The β-motif was identified by Schmidt as a distinct structure type even though not many structures were solved at the time.[1,3] Examination of the vastly more extensive literature today with the Cambridge Database confirms the pronounced paucity of planar aromatic structures with axes between 4.2 and 4.7 Å. This crystallographic 'gap' is indicative of important differences between β and non-β packings. In the former, a molecule is mostly stabilised by its two 4 Å translated (and therefore parallel) neighbours. In the latter, more uniform stabilisation is obtained from a larger number of non-parallel neighbours.[4] So, the non-β structure is obtained for aromatics by the use of glides and screw axes, that is by optimising C....H interactions which are most effective between inclined molecules. In contrast, the β-structure may be engineered through in-plane interactions (Cl....Cl, C-H....O) which result in the adoption of two-dimensional molecular motifs (sheets, ribbons). Since van der Waals stacking of such motifs to optimise C....C contacts is the only manner of extending the structure into the third dimension, these interactions are the basis of the well-known 'β-steering' abilities of groups such as chloro[1] or methylenedioxy[5] when they are substituted on aromatic rings.

Contacts of the Cl....Cl or C-H....O type involve weak intermolecular bonding and it is only recently that even their terminology as 'bonds' has been accepted without scepticism.[6] What is significant, however, is not their magnitude but directionality. In a 4 Å β-structure, these weak contacts are *interstack* and the crystal engineering of such a structure is governed by them even though the major energy stabilisation is through the *intrastack* C....C interactions.[7] This is shown schematically below:



Representation of a β-structure for a planar aromatic compound. Hetero atoms are indicated as heavy circles. Interstack forces are shown as dashed lines. Intrastack C....C forces are along the 4 A° direction and are not shown.

The fact that sulphur forms directional interactions, like chlorine and oxygen, is not new[8] but the importance of such interactions in designing organic materials has again not been fully appreciated or exploited by chemists in general. Here, we have extended our earlier studies on the crystal engineering of β-structures to contacts involving sulphur. This study arose from the crystal structure determination of the thione 1, which has a non-β packing with short axis 6.21 Å and which will be reported elsewhere.[9] It was noted that molecules of 1, though non-planar (interplanar dihedral angle 35°), crystallise in 'corrugated' sheets. While 4 Å stacking of such sheets to obtain a β-structure is not possible perhaps because of the molecular non-planarity, it was felt that the structure seemed to 'tend' towards the β-motif because of its sheetlike character. Accordingly, the 4-phenyl-Δ-4-thiazolene-2-thione system was tentatively identified as one which could lead to the β-structure and the chloro derivative 2 was prepared. The latter compound adopts the β-structure and this paper is concerned with its solid state chemistry.



1, R = H

2, R = Cl

Results and Discussion

Molecular and Crystal Structure of Thione 2: Figure 1 shows the bond lengths and angles while Figure 2 gives the packing of the molecules as viewed down the short axis. Both molecules in the asymmetric unit (interplanar dihedral angles 27° and 31°) exist as the thione tautomer. Our structure determination thus clarifies some of the older uncertainties concerning the tautomerism of the phenyl thiazolene thione system.[10] The molecules are C=S....H-N hydrogen bonded around distinct inversion centres (N....S 3.29 and 3.33 Å). Such hydrogen bonding was also observed for thione 1[9] and has been previously reported for '2-mercaptobenzothiazole'.[11] Symmetry independent hydrogen bonded dimers are further held together by short S....S contacts of 3.41 Å to generate linear ribbons of molecules which extend along [120]. These contacts are between a thione and heterocyclic sulphur atom. Adjacent screw-related ribbons are additionally linked through short S....Cl contacts of 3.54 Å.

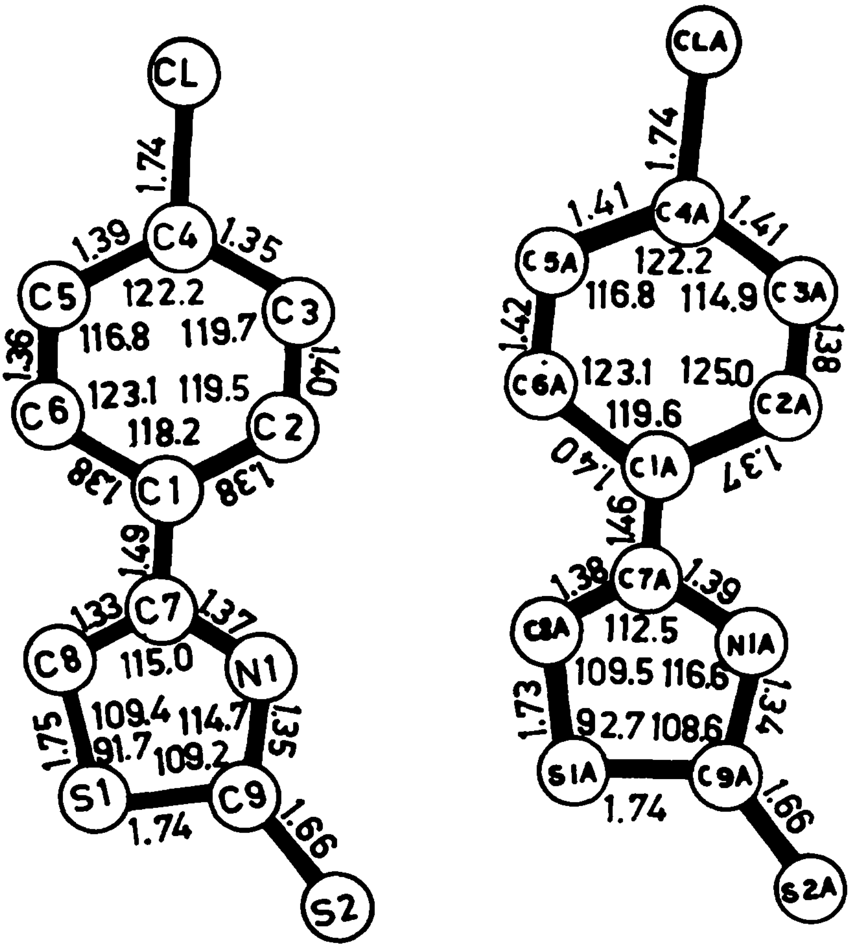


Figure 1.

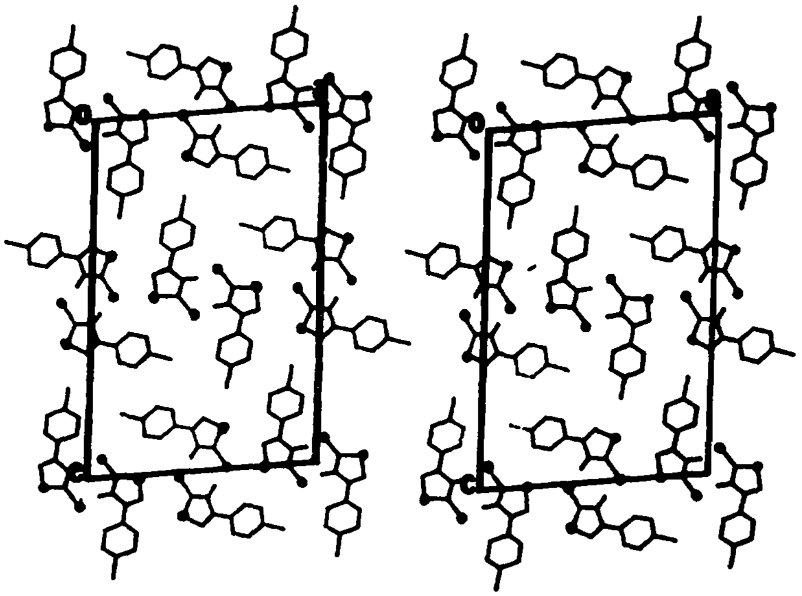
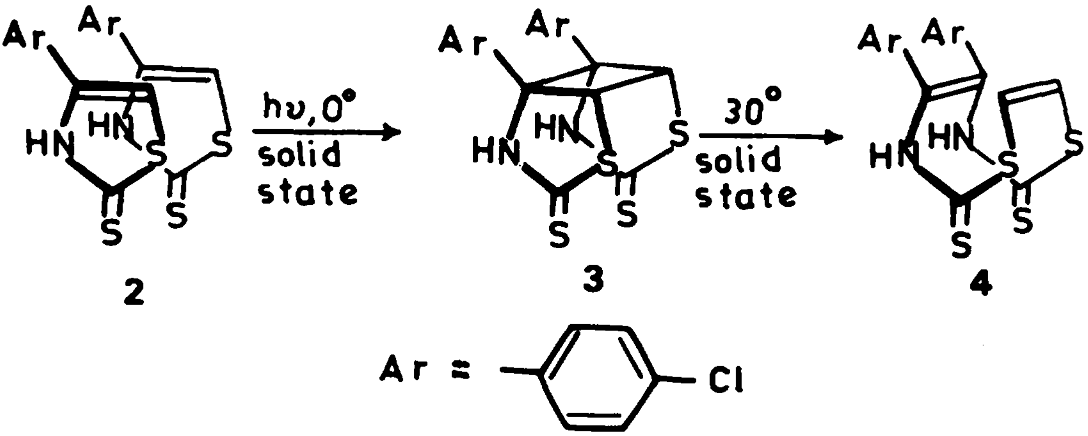


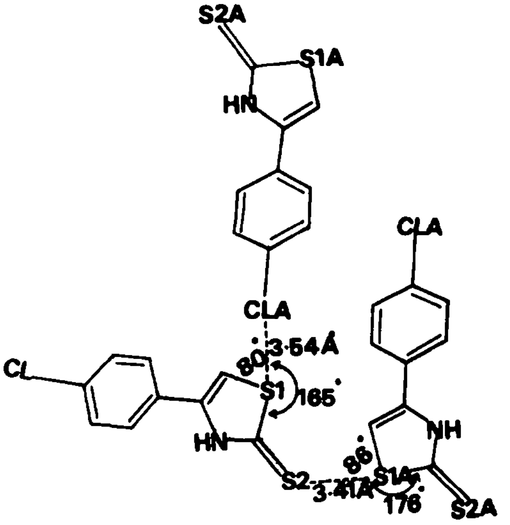
Figure 2.

Solid State Photochemical Reactivity: For the relatively small number of heterocycles where solid state 2+2 cycloadditions have been reported, the heterocyclic group usually plays only an incidental role. In, for instance, 3-methyl-4-nitro-5-styrylisoxazole, 2-thienylacrylic acid or α-benzylidene-γ-butyrolactone, the heterocyclic group is only an appendage to the reactive moiety and is unchanged upon photoreaction.[12] However, the 'potentially reactive' C=C bond in 2 is actually a part of the heterocyclic residue and it was therefore of interest to examine the material further. Irradiation at 0°C of crystalline 2 with either sunlight or an Hg lamp led to rapid reaction with all starting material consumed. Spectral data on the product confirmed that the topochemical dimer 3 was formed quantitatively. Such solid state transformations involving heterocyclic rings are unusual and have been reported only for thymine and coumarin derivatives and some related compounds.[13]



The isolation and purification of dimer 3 had to be carried out at low temperatures. These precautions were necessary since 3 is extremely reactive and collapses to a stabler compound which was unequivocally characterised as the novel ten-membered ring diolefin 4. The latter was also obtained in the solid state when 2 was irradiated at room temperature but always with 3. Though 4 is stabler than 3, it still decomposes slowly in solution to uncharacterised products. It is, however, stable to solid state irradiation at either 0° or 30°C. These experiments indicate that 4 must arise thermally from 3 and this is understandable in view of the strained ring structure in 3.

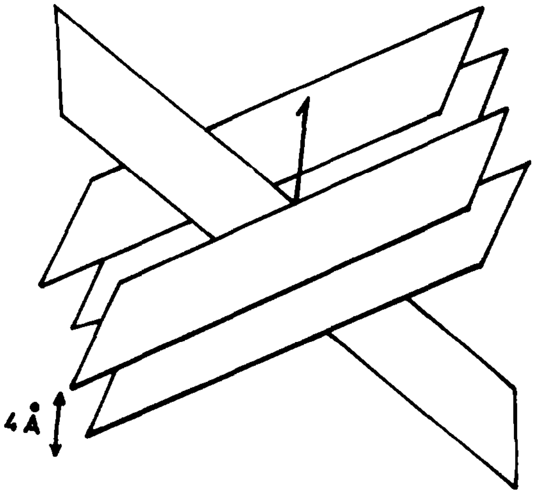
Crystal Engineering: It may be noted that both the S....S and S....Cl contacts in the structure of thione 2 are significantly shorter than the van der Waals values (radii: S, 1.85 Å; Cl, 1.80 Å) and that their angular preferences are almost exactly that predicted by a nucleophile-electrophile model.[8] Thus heterocyclic



Intermolecular S....S and S....Cl contacts for thione 2. Note the approach of the nucleophilic atoms towards heterocyclic sulphur. Note also that both contacts are between symmetry independent molecules.

sulphur seems to behave as an electrophile with respect to both thione sulphur and chlorine in that the non-bonded contacts from these latter atoms are almost along the far side of one of the heterocyclic C-S bonds. The pertinent geometrical parameters are shown above. These directional preferences are well-substantiated in the crystallographic literature. What is important here is that such non-bonded contacts lie nearly in the heterocyclic ring planes. Therefore these contacts are *interstack* and may be either ribbon-generating (S....S) or ribbon linking (S....Cl) and as such significant from the viewpoint of crystal engineering.[7]

Figure 2 shows that the consequence of these S....S and S....Cl contacts is to generate a two-dimensional array of skewed, alternating linear ribbons. The β-structure arises from a 4 Å stacking of this array. The linear ribbon structure is, in fact, a common one for β-compounds and is one of the possibilities in a monoclinic space group when the 4 Å axis coincides with the unique direction.[14] This is indeed seen to be the case for thione **2**. The structure of **2** bears a close resemblance to that of the prototype β-crystal hexachlorobenzene. Here too, the short axis is along the monoclinic direction but Cl....Cl contacts perform the dual functions of ribbon-forming and ribbon-linking.[4]



Schematic view of a linear ribbon β-structure. The unique axis is indicated.

Since thione **1** is a non-β crystal while **2** has a 4 Å axis, a significant question is whether the β-steering is merely because of the chlorine atom.[4,7,14] Curiously no short Cl....Cl contacts are observed in the structure of **2**. So the role of the chloro group in directing the packing of **2** is unlike its behaviour in simpler chloro-aromatics and suggests perhaps that Cl....S and S....S interactions are of greater significance energetically than Cl....Cl ones. Further, in all β-structures arising from Cl....Cl interactions, more than one Cl atom per molecule is usually present. These observations suggest that S, Cl and perhaps N atoms are all required for the β-packing to be adopted here. A more subtle effect which seems to be still difficult to formulate is the effect of the C:H atomic ratio on the structure type adopted.[15] Qualitatively, it has been noted that there is a greater tendency for β-structure adoption when the C:H ratios are larger, though it must be added that molecular planarity and the presence or absence of particular functional groups also play an important role. It might well be that the introduction of the chloro substituent in **2** is just sufficient to raise the C:H ratio above a certain threshold and into the β-domain.

The β-crystal structure of thione **2** does not seem to be a stray observation and a survey of the literature reveals that several other sulphur heterocycles adopt this mode.[16] Some representative examples are benzothienobenzothiophene (S....S, 3.64 Å), benzo-2,1,3-thiadiazole (S....S, 3.85 Å), 2-thienylacrylic acid (S....S, 3.89 Å), thioindigo (S....S, 3.78 Å), TTF-TCNQ (S....N, 3.20 Å) and benzothiopyrone. The *interstack* contacts have been given and they rather than the intrastack contacts may well play a dominant role in all these structures. Another relevant compound is the superconductor $(BEDT\text{-}TTF)_2I_3$ where the interstack S....S contacts (< 3.60 Å) are again *shorter* than the intrastack ones.[17]

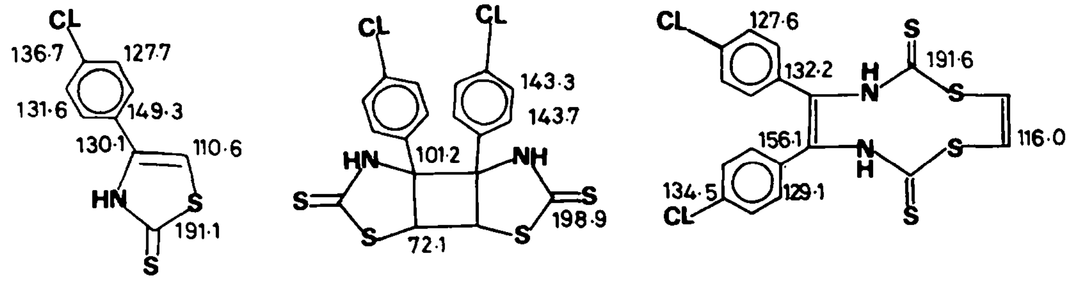
A consideration of these and other compounds shows that the scope of crystal engineering of 4 Å β-structures may be significantly enlarged to include heterocyclic sulphur compounds and that novel physical properties and solid state reactivity patterns may, as a consequence, be made to emerge. Extensions to other chalcogen heterocycles may naturally be anticipated since Se....Se or Te....Te bonding will, if at all, be more significant.

Experimental Section

4-(4'-chloro)-phenyl- Δ-4-thiazolene-2-thione, 2: To a solution of freshly prepared ammonium dithiocarbonate[18] in ethanol (12 g in 400 ml) were added 16 g of 4-chlorophenacyl bromide. The mixture was refluxed for 3 h, well shielded from light. Solid NH_4Br separated out at the end of the reaction and was filtered off. Most of the ethanol was removed under reduced pressure and the residue washed several times with 1:1 hexane-benzene to leave the pure thione as the insoluble portion. Yield 15.6 g (68%), mp 210-212°C (lit 212°C).[19] Crystals suitable for X-ray diffraction were obtained by careful recrystallisation from 1:10 acetone-hexane. UV, $\lambda_{max.}$ (MeOH) 242, 282 nm(sh); IR (KBr) 1455, 1060 cm^{-1}, C = S; NMR (dmso-d_6) δ 3.5 (s,1H), 7.2(s,1H), 7.9-8.8(q,AA'BB',4H); ^{13}C NMR (dmso-d_6) 110.6, 127.7, 130.1, 131.6, 136.8, 149.3, 191.1 ppm.

Solid state photoirradiation of thione 2: Crystalline thione 2 (0.5 g) was irradiated at 0°C between glass plates with a Hg lamp (Hanovia, 450 W). The reaction was followed by tlc (4:1 hexane-EtOAc) and was found to be quantitative in 2 h. The reaction mixture was separated by preparative tlc using the same solvent system. The fractions were dissolved in acetone which was later removed under reduced pressure without heating so as to avoid thermal decomposition. Dimer 3 was the sole product. IR(KBr) 1480, 1060 C=S, 935 cm^{-1} cyclobutane C-H bend; NMR ($CDCl_3$) δ 5.9(s,2H cyclobutane); 7.5-7.8(q,AA'BB',8H); ^{13}C NMR ($CDCl_3$) 72.1, 101.2, 143.7, 143.7, 198.9 ppm.

When dimer 3 was warmed to 30-35°C or if the irradiation was carried out at ambient temperatures or under sunlight, diolefin 4 was produced and was easily separated by preparative tlc (hexane-EtOAc) as a pure white solid, mp 118°C; IR(KBr) 1475, 1090, 1040, 825, 640 cm^{-1}; NMR($CDCl_3$) δ 7.4(s,2H), 7.5-7.8 (q,AA'BB', 8H); ^{13}C NMR ($CDCl_3$) 116.0, 127.6, 129.1, 132.2, 134.5, 156.1, 191.6 ppm; MS m/z (%) 452(8.9), 454(7.7), 456(2.1) all $M\text{-}2H^{+\bullet}$; 227(100), 229(42.5) both $(M/2^{+\bullet})$.



2 3 4

^{13}C NMR Spectral Assignments for compounds 2, 3 and 4.

X-Ray structure Determination of 4-(4'-chloro)-phenyl-Δ-4-thiazolene-2-thione, 2: Crystal data, C_9H_6ClNS, M=277.5, monoclinic, space group $P2_1/n$, a=17.327(4), b=3.950(2), c=27.877(6) Å, β=93.88(2)°, V=1903(2) $Å^3$, F(000)=928, Z=8, D_c=1.46 g cm^{-3}, D_m=1.49 g cm^{-3}, μ (Mo-K_α)=7.12. The crystals were extremely light sensitive and the data, collected on an Enraf Nonius CAD-4 diffractometer over a 36 h period, showed no significant crystal decomposition. A total of 783 independent reflections was considered significant at the 2.0σ level out of the 2271 collected. The structure was solved by the routine application of MULTAN80 and refined anisotropically using block-diagonal procedures with SHELX76 with the hydrogen atoms placed in calculated positions. The final R value was 0.050 with R_w being 0.044. The weights were taken as $0.9299/[(\sigma(F_o))^2+(0.02\ F_o)^2]$. The final electron density difference map did not reveal any significant electron density above 0.12 $eÅ^{-3}$ or below -0.16 $eÅ^{-3}$. The final atomic co-ordinates for thione 2 are listed in Table 1.

Table 1. Atomic co-ordinates in fractional crystal co-ordinates for thione 2.§

Atom	x	y	z
C(1)	1.2162(7)	0.4995(30)	0.6343(4)
C(2)	1.1857(7)	0.4797(36)	0.6037(4)
C(3)	1.2587(7)	0.6076(38)	0.6182(4)
C(4)	1.2719(6)	0.7247(39)	0.6637(4)
C(5)	1.2131(7)	0.7596(33)	0.6979(4)
C(6)	1.1425(7)	0.6321(39)	0.6798(4)
C(7)	1.0477(6)	0.3681(34)	0.6189(4)
C(8)	1.0009(7)	0.2281(37)	0.6494(4)
C(9)	0.9478(6)	0.2403(33)	0.5639(4)
Cl	1.3639(2)	0.8737(12)	0.6836(1)
N(1)	1.0193(5)	0.3737(29)	0.5719(3)
S(1)	0.9152(2)	0.1007(10)	0.6180(1)
S(2)	0.8960(2)	0.2079(12)	0.5119(1)
H(8)	0.9873(7)	0.3102(37)	0.6776(4)
HN(1)	1.0508(5)	0.4762(29)	0.5414(3)
C(1)A	0.3561(7)	0.4574(33)	0.3785(4)
C(2)A	0.2969(7)	0.5897(37)	0.3494(5)
C(3)A	0.3060(7)	0.7050(37)	0.3030(5)
C(4)A	0.3778(8)	0.6727(40)	0.2860(4)
C(5)A	0.4418(7)	0.5478(35)	0.3145(4)
C(6)A	0.4298(6)	0.4307(34)	0.3615(4)
C(7)A	0.3430(7)	0.3429(37)	0.4272(4)
C(8)A	0.2745(7)	0.2198(38)	0.4428(4)
C(9)A	0.3843(6)	0.2319(34)	0.5064(4)
ClA	0.3942(2)	0.8165(11)	0.2287(1)
N(1)A	0.4019(5)	0.3464(32)	0.4633(3)
S(1)A	0.2883(2)	0.0971(11)	0.5023(1)
S(2)A	0.4413(2)	0.2025(11)	0.5566(1)
H(8)A	0.2191(7)	0.2446(38)	0.4182(4)
HN(1)A	0.4614(5)	0.3543(32)	0.4574(3)

§Estimated standard deviations are given in parentheses. Hydrogen atoms included only if refined.

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