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Structural and spectral studies of *N*-(2-pyridyl)-*N*′-(4-substituted phenyl)thioureas

Lisa F. Szczepura*, Kristin K. Eilts, Ann K. Hermetet, Lily J. Ackerman,
John K. Swearingen, Douglas X. West

Department of Chemistry, Illinois State University, Normal, IL 61790-4160, USA

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Abstract

The following molecules were found to have intramolecular hydrogen bonding between the N′H and the pyridine nitrogen and intermolecular hydrogen bonding between the NH and a thione sulfur of a second molecule to form dimers: *N*-(2-pyridyl)-*N*′-(4-methoxyphenyl)thiourea, PyTu4OMe, triclinic, *P*-1, $a = 7.158(4)$, $b = 8.742(3)$, $c = 10.833(4)$ Å, $\alpha = 70.53(3)$, $\beta = 74.38(3)$, $\gamma = 73.97(4)°$, $V = 635.5(5)$ Å^3 and $Z = 2$; *N*-(2-pyridyl)-*N*′-(4-nitrophenyl)thiourea, PyTu4NO$_2$, monoclinic, $P2_1/c$, $a = 11.670(1)$, $b = 5.9225(9)$, $c = 18.792(4)$ Å, $\beta = 107.99(1)°$, $V = 1244.8(7)$ Å^3 and $Z = 4$; *N*-(2-pyridyl)-*N*′-(4-chlorophenyl)thiourea, PyTu4Cl, triclinic, *P*-1, $a = 9.939(3)$, $b = 11.399(4)$, $c = 12.264(5)$ Å, $\alpha = 65.50(4)$, $\beta = 87.46(3)$, $\gamma = 76.63(3)°$, $V = 1228.1(7)$ Å^3 and $Z = 4$ and *N*-(2-pyridyl)-*N*′-(4-bromophenyl)thiourea, PyTu4Br, triclinic, *P*-1, $a = 10.020(2)$, $b = 11.444(2)$, $c = 12.353(5)$ Å, $\alpha = 64.76(2)$, $\beta = 87.61(3)$, $\gamma = 77.88(2)°$, $V = 1250.8(7)$ Å^3 and $Z = 4$. The methoxy and nitro moieties of PyTu4OMe and PyTu4NO$_2$ also interact with N′H, and there is a weak intermolecular interaction between one of the pyridine hydrogen atoms and the thione sulfur in PyTu4Br. Solution ^{1}H NMR spectral studies (DMSO-d_6) show the N′H resonance considerably downfield for each thiourea and its chemical shift, as well as that of NH, is affected by substituents on the phenyl ring. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Heterocyclic thioureas; Intramolecular hydrogen bonding; Intermolecular hydrogen bonding; Crystal structures; ^{1}H NMR spectroscopy

1. Introduction

A recent structural study has been reported for *N*-(2-pyridyl)-*N*′-(phenyl)thiourea [1] after ^{1}H NMR spectroscopy correctly predicted intramolecular hydrogen bonding between the pyridine nitrogen and N′H for *N*-(2-pyridyl)thioureas [2]. Studies of a number of substituted thioureas, including *N*-(benzoyl)thioureas, indicate intramolecular hydrogen bonding between N′H and the benzoyl oxygen [3–9]. There is also an intermolecular hydrogen bond with the NH and the sulfur of a neighboring molecule to form a two-dimensional network in these latter thioureas [3–8]. In addition, crystal structures of substituted thioureas with intermolecular N–H···S′ bonding, but without intramolecular hydrogen bonding, have been reported [10–14]. More recent studies of substituted *N*-(2-pyridyl)-*N*′-(aryl)thioureas include *N*-2-(4,6-lutidyl)-*N*′-(phenyl)thiourea, 4,6LuTuPh [15], the three *N*-(2-pyridyl)-*N*′-(tolyl)thioureas [16], the three *N*-2-(4,6-lutidyl)-*N*′-(tolyl)thioureas [17] and *N*-(5-bromo-2-pyridyl)-*N*′-[2-(2,5-dimethoxyphenyl)ethyl]thiourea [18]. The present thioureas, like the *N*-(benzoyl)thioureas [3–8], feature both intramolecular

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* Corresponding author. Tel.: +1-309-438-2359; fax: +1-309-438-5538.

E-mail address: lfs@xenon.che.ilstu.edu (L.F. Szczepura).

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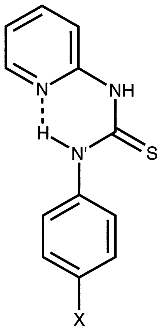

PyTu4X

Fig. 1. Representations of *N*-(2-pyridyl)-*N*′-(4-substituted phenyl) thioureas with expected intramolecular hydrogen bonding (X = OMe, Br, Cl, NO_2).

and intermolecular hydrogen bonding. A recent communication showed that some members of a series of *N*-(2-pyridyl)-*N*′-(2-methoxyphenyl)-thioureas possess bifurcated intramolecular hydrogen bonding to the pyridine nitrogen and methoxy oxygen [19]. In order to determine whether functional groups at other positions of the phenyl ring are involved in hydrogen bonding, we prepared, recorded ^1H NMR spectra of, and obtained the crystal structures and lattice arrangements for four *N*-(2-pyridyl)-*N*′-(4-substituted phenyl)thioureas, Fig. 1.

2. Experimental

2-Aminopyridine and 4-methoxy-, 4-nitro-, 4-chloro- and 4-bromophenyl isothiocyanates were purchased from Aldrich and used as received. 2-Aminopyridine and a 4-substituted phenyl isothiocyanate

Table 1
Crystallographic data and methods of data collection, solution and refinement for PyTu4OMe, $PyTu4NO_2$, PyTu4Cl and PyTu4Br

Crystal data	PyTu4OMe	$PyTu4NO_2$	PyTu4Cl	PyTu4Br
Empirical formula	$C_{13}H_{13}ON_3S$	$C_{12}H_{10}O_2N_4S$	$C_{12}H_{10}ClN_3S$	$C_{12}H_{10}BrN_3S$
Crystal color, habit	Colorless, prism	Yellow, prism	Colorless, prism	Colorless, prism
Crystal size (mm)	0.30 × 0.25 × 0.15	0.25 × 0.20 × 0.12	0.32 × 0.24 × 0.14	0.30 × 0.20 × 0.12
Crystal system	Triclinic	Monoclinic	Triclinic	Triclinic
Space group	*P*-1	$P2_1/c$	*P*-1	*P*-1
a (Å)	7.158(4)	11.670(1)	9.939(3)	10.020(2)
b (Å)	8.742(3)	5.9225(9)	11.399(4)	11.444(2)
c (Å)	10.883(4)	18.792(4)	12.264(5)	12.353(5)
α (°)	70.53(3)	90(0)	65.50(4)	64.76(2)
β (°)	74.38(3)	107.99(1)	87.46(3)	87.61(3)
γ (°)	73.97(4)	90(0)	76.63(3)	77.88(2)
Volume ($Å^3$)	635.5(5)	1244.8(7)	1228.1(7)	1250.8(7)
Z	2	4	4	4
Formula weight	259.3	274.3	263.8	309.2
Density (calcd.) (g/cm^3)	1.355	1.464	1.427	1.642
Absorp. coeff. (mm^{-1})	0.246	0.264	0.461	3.434
F(000)	272	568	544	620
Index ranges	$0 \leq h \leq 9$	$0 \leq h \leq 15$	$0 \leq h \leq 12$	$0 \leq h \leq 13$
	$-11 \leq k \leq 11$	$0 \leq k \leq 7$	$-14 \leq k \leq 14$	$-14 \leq k \leq 14$
	$-14 \leq l \leq 14$	$-24 \leq l \leq 24$	$-15 \leq l \leq 15$	$-16 \leq l \leq 16$
Reflections collected	3227	3401	6215	6278
Independent reflections	3126	2858	5620	5723
Observed reflections	1433 $\{I > 3.0\sigma(I)\}$	2412 $\{I > 3.0\sigma(I)\}$	3893 $\{I > 3.0\sigma(I)\}$	3002 $\{I > 3.0\sigma(I)\}$
Absorption correction	None	ψ-scan	ψ-scan	ψ-scan
Max. and min. transmissions		0.993 and 0.967	1.000 and 0.942	1.000 and 0.838
Goodness-of-Fit	0.474	1.216	1.324	2.946
Largest diff. peak ($eÅ^{-3}$)	0.25	0.60	0.49	0.99
Largest diff. hole ($eÅ^{-3}$)	− 0.16	− 0.32	− 0.33	− 1.33
R, *wR*	0.0332, 0.0329	0.0485, 0.0688	0.0484, 0.0733	0.0637, 0.0922
R, *wR* (all reflections)	0.2697, 0.2654	0.0623, 0.0859	0.0859, 0.1313	0.1443, 0.1426

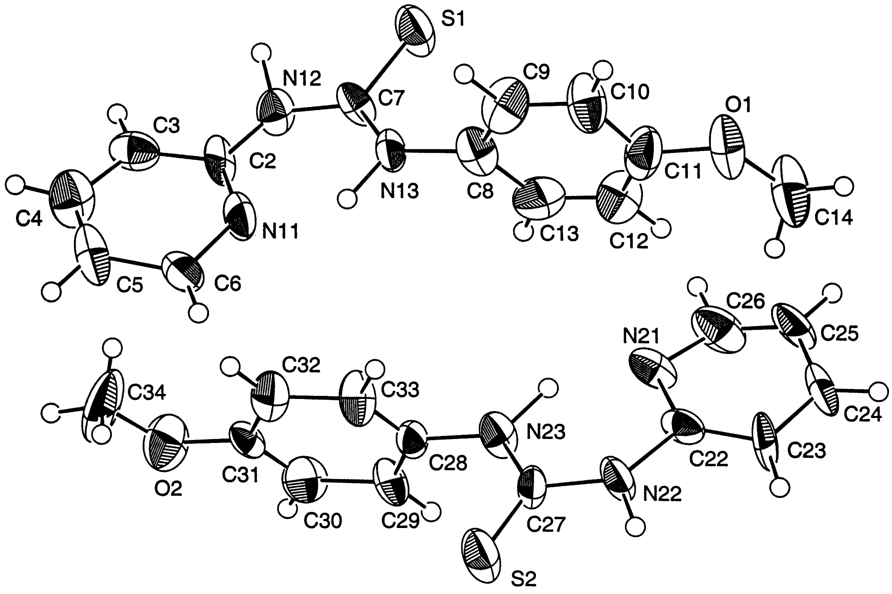

Fig. 2. ORTEP diagram showing the two unique molecules of PyTu4OMe with atom numbering scheme and displacement ellipsoids at 50% probability level.

were dissolved in a 1:1 molar ratio in 95% ethanol, and the resulting mixture gently refluxed for a minimum of 1 h. On cooling and slowly evaporating (35°C) the reactant mixture, the thioureas crystallized from solution. The solids were filtered, washed with cold isopropanol followed by anhydrous ether, dried on a warm plate and then stored until required for characterization. The yields are ca. 75% for each of the thioureas and the melting points are as follows: PyTu4OMe, 187–190°C; PyTu4NO_2, 175–178°C; PyTu4Cl, 190–193°C and PyTu4Br, 202–204°C. Their ^1H NMR spectra were recorded in DMSO-d_6 with a Varian Mercury 400 MHz spectrophotometer. ^1H NMR data (DMSO-d_6): PyTu4OMe 3.76 (s, 3H), 6.94 (d, 2H), 7.08 (dd, 1H), 7.24 (d, 1H), 7.51 (d, 2H), 7.82 (m, 1H), 8.29 (dd, 1H), 10.82 (s, 1H, NH), 13.58 (s, 1H, N′H). PyTu4Cl: 7.12 (dd, 1H), 7.25 (d, 1H), 7.44 (d, 2H), 7.74 (d, 2H), 7.84 (m, 1H), 8.32 (dd, 1H), 10.99 (s, 1H, NH), 13.91 (s, 1H, N′H). PyTu4Br: 7.11 (dd, 1H), 7.25 (d, 1H), 7.57 (d, 2H), 7.70 (d, 2H), 7.84 (m, 1H), 8.32 (dd, 1H), 10.99 (s, 1H, NH), 13.92 (s, 1H, N′H). PyTu4NO_2: 7.15 (dd, 1H), 7.28 (d, 1H), 7.87 (m, 1H), 8.16 (d, 2H), 8.25 (d, 2H), 8.37 (dd, 1H), 11.20 (s, 1H, NH), 14.48 (s, 1H, N′H).

Prismatic crystals of the thioureas were grown by slow evaporation of acetone–ethanol solutions (1:1 by volume) at room temperature. Crystals were mounted on glass fibers and used for data collection at 293 K on a Nonius MACH3 automatic diffractometer, MoKα ($\lambda = 0.71073$ Å). Cell constants and an orientation matrix for data collections were obtained by least squares refinements of the diffraction data from 25 reflections. The structures were solved with direct methods and missing atoms were found by difference-Fourier synthesis. All non-hydrogen atoms were refined with anisotropic temperature factors and hydrogens attached to nitrogens were found on the difference-Fourier map. The H atoms of CH were fixed at $d = 0.96$ Å, allowed to ride on the C atoms and assigned fixed isotropic temperature factor, $U = 0.05$ Å^2. The coordinates of the H atoms attached to N and N′ were refined isotropically. Refinement of the structures was made by full-matrix least-squares on F. Scattering factors are from Wassmaire and Kirfel [20], calculations were done by MAXUS, version 2.0 [21], and graphics are PLATON for Windows [22].

3. Results and discussion

3.1. Structural studies

The crystallographic data, as well as the solution

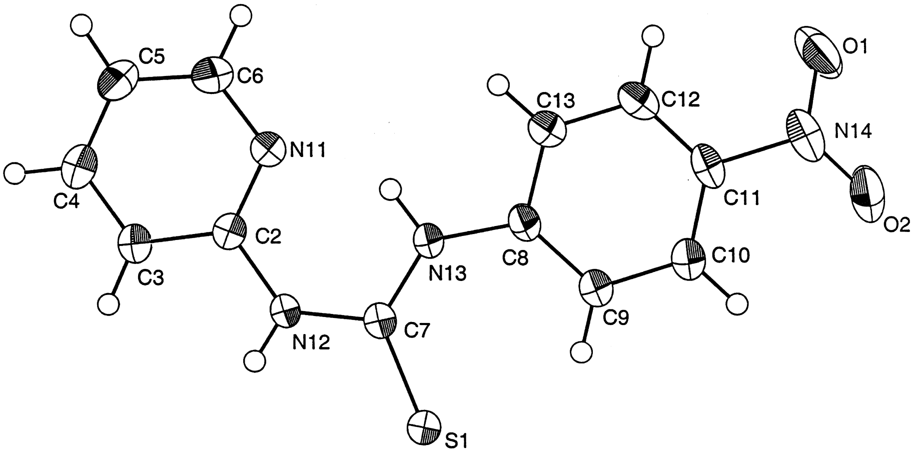

Fig. 3. ORTEP diagram showing $PyTu4NO_2$ with atom numbering scheme and displacement ellipsoids at 50% probability level.

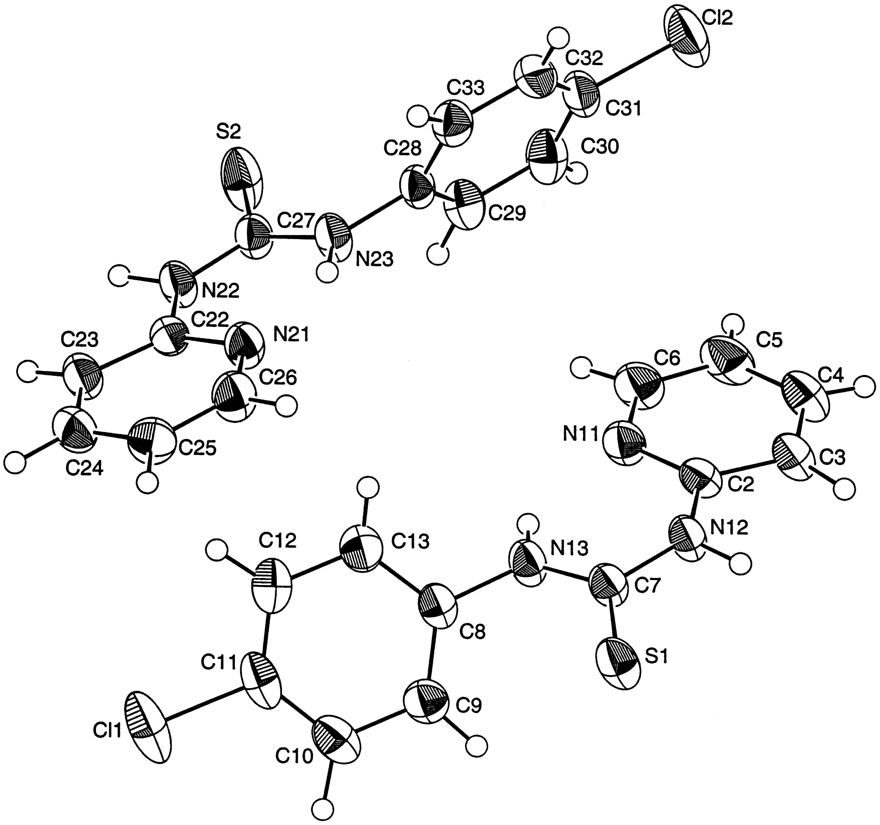

Fig. 4. ORTEP diagram showing the two unique molecules of PyTu4Cl with atom numbering scheme and displacement ellipsoids at 50% probability level.

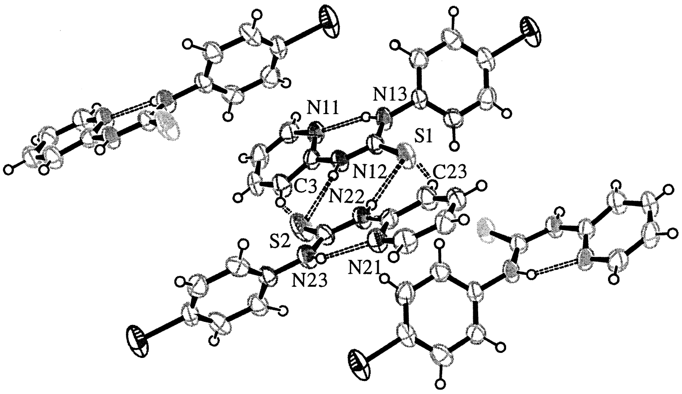

Fig. 5. Packing diagram of PyTu4Br showing intramolecular and intermolecular hydrogen bonding.

and refinement information for these thioureas, are shown in Table 1, and the atomic coordinates and equivalent isotropic displacement coefficients are included in the deposited material (see Section 4), as are a complete list of bond distances and angles.

The molecular structures are represented by the ORTEP diagrams of PyTu4OMe, PyTu4NO_2 and PyTu4Cl shown in Figs. 2–4, respectively. Fig. 5 shows the packing diagram for PyTu4Br with the intermolecular and intramolecular hydrogen bonding indicated. These thioureas are in a conformation resulting from intramolecular hydrogen bonding of N′H to the pyridine nitrogen, in a manner similar to the *N*-(benzoyl)thioureas [3–8] and the *N*-(2-pyridyl)-*N*′-(tolyl)thioureas [16]. Three of the reported thioureas (all but PyTu4NO_2) crystallize in the P-1 symmetry group with two crystallographically unique molecules. Inspection of Table 2 shows that the bonds of the two unique molecules of PyTu4OMe have a number of significantly different distances, but the two molecules of PyTu4Cl and PyTu4Br have similar bond distances. However, the average bond distances for PyTu4OMe are in good agreement with the distances for the other three thioureas of this study

Table 2

Selected bond distances (Å) and angles (°) for PyTu4OMe, PyTu4NO_2, PyTu4Cl and PyTu4Br. The second column represents the analogous bonds in the S2 molecule of PyTu4OMe, PyTu4Cl and PyTu4Br

Distances (Å)	PyTu4OMe	PyTu4NO_2	PyTu4Cl	PyTu4Br
S1–C7	1.72(2) 1.65(2)	1.681(4)	1.688(5) 1.684(5)	1.68(2) 1.69(2)
N11–C2	1.28(2) 1.35(3)	1.332(5)	1.338(7) 1.336(7)	1.34(2) 1.35(2)
N11–C6	1.39(3) 1.39(2)	1.349(6)	1.348(7) 1.346(7)	1.35(2) 1.35(2)
N12–C2	1.35(2) 1.47(2)	1.399(5)	1.404(6) 1.411(6)	1.42(2) 1.41(2)
N12–C7	1.32(2) 1.41(2)	1.370(5)	1.372(7) 1.370(7)	1.35(2) 1.35(2)
N13–C7	1.29(2) 1.37(2)	1.355(5)	1.337(7) 1.337(7)	1.36(2) 1.35(2)
N13–C8	1.45(3) 1.42(3)	1.406(5)	1.435(8) 1.434(8)	1.44(2) 1.43(2)
Angles (°)				
C2–N12–C7	128.9(13) 130.3(12)	130.7(4)	130.0(5) 129.9(5)	130.5(10) 130.0(10)
C7–N13–C8	128.0(12) 120.5(12)	131.6(3)	126.8(4) 124.7(4)	124.6(9) 127.5(9)
N11–C2–N12	124.4(14) 114.5(12)	119.1(4)	118.8(4) 119.0(5)	118.4(10) 118.4(10)
N12–C2–C3	116.9(14) 118.2(12)	117.6(4)	118.2(4) 118.2(4)	118.3(11) 118.1(10)
S1–C7–N12	122.1(10) 114.6(10)	117.3(3)	118.9(4) 118.5(4)	119.1(9) 119.1(9)
S1–C7–N13	119.3(10) 126.9(11)	127.1(3)	124.6(4) 123.8(4)	123.6(9) 123.6(9)
N12–C7–N13	118.6(11) 118.3(12)	115.2(4)	116.5(4) 117.7(5)	117.3(10) 117.3(10)
N13–C8–C9	122.5(14) 118.2(13)	126.4(4)	121.0(5) 120.8(5)	120.7(11) 120.2(11)
N13–C8–C13	122.3(15) 117.7(15)	114.2(4)	117.7(5) 118.0(5)	117.2(11) 118.4(11)

Table 3
Comparison of selected bond distances (Å) and bond angles (°) for *N*-(2-pyridyl)-N'-(phenyl)thiourea and *N*-(2-pyridyl)-N'-(4-substituted phenyl)thioureas

	Bond distances, Å			Bond angles, °			
Compound	N12–C7	S1–C7	N13–C7	N12–C7–N13	N12–C7–S1	N13–C7–S1	Ref
PyTu4OMe	1.365(20)	1.685(20)	1.33(2)	118.4(12)	118.4(10)	123.1(11)	[a]
PyTu4NO$_2$	1.370(5)	1.681(4)	1.355(5)	115.2(4)	117.3(3)	127.1(3)	[a]
PyTu4Cl	1.371(7)	1.686(4)	1.337(7)	116.3(4)	117.5(3)	126.1(3)	[a]
PyTu4Br	1.35(2)	1.685(20)	1.355(20)	117.3(10)	119.1(9)	123.6(9)	[a]
PyTu4T[b]	1.376(5)	1.678(4)	1.340(6)	116.2(7)	118.8(6)	125.0(6)	16
PyTuPh[c]	1.374(4)	1.682(3)	1.335(4)	116.8(5)	118.6(4)	124.6(4)	1

[a] This work.
[b] *N*-(2-pyridyl)-N'-(4-tolyl)thiourea.
[c] *N*-(2-pyridyl)-N'-(phenyl)thiourea.

and are within three orders of magnitude of their combined estimated standard deviations. The bond angles of the two molecules of PyTu4OMe also show some variation, however, as with the bond lengths, the average bond angles of the two molecules of PyTu4OMe are in good agreement with the other three thioureas of this study. The greatest differences in angles for the four thioureas occur for N13–C8–C9 and N13–C8–C13; the difference between these two angles (i.e. $\angle$N13–C8–C9–$\angle$N13–C8–C13) is largest for PyTu4NO$_2$, 12.2(4)° followed by PyTu4Br, 3.5(11)°, PyTu4Cl, 3.3(5)°, and PyTu4OMe has essentially no difference. The previously reported PyTu4T, *N*-(2-pyridyl)-N'-(4-tolyl)thiourea, has a value of 3.1(7)° [16] for this difference. Thus, the electronic effect of the 4-substituent attached to the aryl ring affects the structural nature of these thioureas. The C11(31)–X (X = OMe, NO$_2$, Cl, Br) average bond distances are 1.39(3), 1.474(5), 1.751(6) and 1.92(2) Å for PyTu4OMe, PyTu4NO$_2$, PyTu4Cl

Table 4
Angles between mean planes for PyTu4OMe, PyTu4NO$_2$, PyTu4Cl and PyTu4Br. Plane A(D) = mean plane of pyridine ring, plane B(E) = mean plane of the thiourea moiety, N–C(S)–N', and plane C(F) = mean plane of the phenyl ring

Compound	Plane	Plane	Mean plane deviation	Atom with greatest deviation	Plane/Plane	Angle
PyTu4OMe	N11–C2–C3–C4–C5–C6	A	0.0006	C6, 0.0632(0.0166)	A/B	5.7(0.2)
	N12–C7–S1–N13	B	0.0010	C7, 0.0167(0.0125)	B/C	85.8(5.2)
	C8–C9–C10–C11–C12–C13	C	0.0051	C12, 0.0488(0.0147)	A/C	86.9(3.0)
	N21–C22–C23–C24–C25–C26	D	0.0063	C26, 0.0952(0.0167)	D/E	1.3(0.1)
	N22–C27–S2–N23	E	0.0083	S2,0.0413(0.000)	E/F	83.5(2.4)
	C28–C29–C30–C31–C32–C33	F	0.0035	C31, 0.0374(0.0220)	F/D	83.5(2.8)
PyTu4NO$_2$	N11–C2–C3–C4–C5–C6	A	0.0001	C3, 0.0067(0.0042)	A/B	11.2(0.4)
	N12–C7–S1–N13	B	0.0003	C7, 0.0030(0.0034)	B/C	8.2(0.2)
	C8–C9–C10–C11–C12–C13	C	0.0002	C13, 0.0049(0.0038)	A/C	19.4(0.6)
PyTu4Cl	N11–C2–C3–C4–C5–C6	A	0.0004	C6, 0.0088(0.0062)	A/B	11.3(0.4)
	N12–C7–S1–N13	B	0.0006	C7, 0.0061(0.0050)	B/C	57.9(1.8)
	C8–C9–C10–C11–C12–C13	C	0.0001	C9, 0.0043(0.0052)	A/C	60.4(2.1)
	N21–C22–C23–C24–C25–C26	D	0.0003	C26, 0.0114(0.0059)	D/E	1.9(0.1)
	N22–C27–S2–N23	E	0.0001	C27, 0.0005(0.0051)	E/F	57.1(2.1)
	C28–C29–C30–C31–C32–C33	F	0.0001	C33, 0.0063(0.0052)	F/D	58.7(1.6)
PyTu4Br	N11–C2–C3–C4–C5–C6	A	0.0007	C6, 0.0173(0.0139)	A/B	1.1(0.1)
	N12–C7–S1–N13	B	0.0004	C7, 0.0073(0.0149)	B/C	55.7(1.6)
	C8–C9–C10–C11–C12–C13	C	0.0001	C12, 0.0079(0.0125)	A/C	56.7(2.0)
	N21–C22–C23–C24–C25–C26	D	0.0004	C26, 0.0073(0.0149)	D/E	10.8(0.2)
	N22–C27–S2–N23	E	0.0003	C27, 0.0022(0.0124)	E/F	58.3(1.8)
	C28–C29–C30–C31–C32–C33	F	0.0001	C32, 0.0092(0.0127)	F/D	60.0(1.8)

Table 5
Intramolecular and intermolecular hydrogen bond distances (Å) and angles (°) for the various *N*-(2-pyridyl)-*N*′-(4-substituted phenyl)thioureas (D = donor, A = acceptor)

Intramolecular						
Thiourea	D	A	D–H	H···A	D–H···A	∠(D–H···A)
PyTu4OMe	N13	N11	1.13(2)	1.75(2)	2.68(2)	136.8(8)
	N23	N21	1.16(2)	1.70(2)	2.70(2)	140.2(8)
PyTu4NO$_2$	N13	N11	0.922(3)	1.849(4)	2.655(5)	144.7(3)
PyTu4Cl	N13	N11	0.812(4)	2.012(4)	2.664(6)	139.6(4)
	N23	N21	0.967(4)	1.842(4)	2.673(6)	142.2(3)
PyTu4Br	N13	N11	0.974(9)	1.94(1)	2.66(2)	128.7(7)
	N23	N21	0.960(9)	1.87(1)	2.66(2)	137.1(7)
Intermolecular						
Thiourea	D	A	D–H	H···A	D–H···A	∠(D–H···A)
PyTu4OMe	N12	S2	1.12(2)	2.473(0)	3.42(2)	141.6(7)
	N22	S1	1.04(2)	2.454(2)	3.41(1)	152.6(7)
	N13	O2	1.13(2)	3.19(1)	3.82(1)	116.0(7)
	N23	O1	1.16(2)	3.05(2)	3.62(1)	110.3(7)
PyTu4NO$_2$	N12	S1	0.865(4)	2.576(1)	3.414(3)	163.6(3)
	N13	O1	0.922(3)	3.247(4)	3.333(5)	120.2(1)
PyTu4Cl	N12	S2	0.948(5)	2.443(2)	3.322(5)	154.2(3)
	N22	S1	0.954(5)	2.557(2)	3.504(5)	171.5(3)
PyTu4Br	N12	S2	0.96(1)	2.563(4)	3.51(1)	168.9(6)
	N22	S1	0.96(1)	2.391(4)	3.32(1)	163.3(6)
	C3	S2	0.98(2)	2.915(3)	3.80(1)	151.6(7)
	C23	S1	0.97(2)	2.681(4)	3.51(1)	144.2(7)

and PyTu4Br, respectively. The O–C14(34) bond distance for PyTu4OMe is 1.42(3) Å, the two N–O bond distances of PyTu4NO$_2$ are 1.224(5) and 1.229(6) Å and the O–N–O bond angle is 124.2(4)°.

A comparison of the bond distances and angles of the thiourea moiety of the four complexes of this study and *N*-(2-pyridyl)-*N*′-(phenyl)thiourea [1] and *N*-(2-pyridyl)-*N*′-(4-tolyl)thiourea, PyTuPh and PyTu4T [16], is shown in Table 3. There are no significant differences in the bond distances, but the two NCS bond angles (N12–C7–S1 or N13–C7–S1) show some variation. However, this variation does not appear to be related to the electronic effects of the functional groups on the aryl ring; the angles for PyTu4NO$_2$ and PyTu4Cl show the largest difference.

Listed in Table 4 are the mean plane deviations for the pyridine ring, the thiourea moiety and the phenyl ring along with the angles between planes and the atom deviating to the greatest extent for each plane. For the four thioureas and their crystallographically unique molecules the angle between the pyridine ring and the thiourea moiety ranges from 1.1(0.1) to 11.3(0.4)° (mean plane angles A/B and D/E in Table 4) consistent with N13H13···N11 (and N23H23···N21) intramolecular hydrogen bonding (vide infra). However, the angle between the mean planes of the thiourea moiety and the phenyl ring is larger for most of these thioureas (mean plane angles B/C and E/F in Table 4). The average of the two unique molecules is 84.7(5.2), 57.5(2.1) and 57.0(1.8)° for PyTu4OMe, PyTu4Cl and PyTu4Br, respectively. However, the angle between the mean planes of the thiourea moiety of PyTu4NO$_2$ and the phenyl ring is much smaller, 8.2(0.2)°, and between the pyridine and phenyl rings is 19.4(0.6)° (mean plane angles A/C and D/F in Table 4) showing that this molecule is the most planar of the four thioureas studied here.

The various modes of hydrogen bonding are shown in Table 5. As found for the *N*-(2-pyridyl)thioureas previously [2,15–17,19], intramolecular hydrogen bonding between N13H13(N23H23) and N11(N21) occurs with an N13···N11 (N23···N21) distance of about 2.7 Å and an N13–H13···N11 (N23–H23···N21) angle of about 140°. The small angle between the mean planes of the pyridine ring and

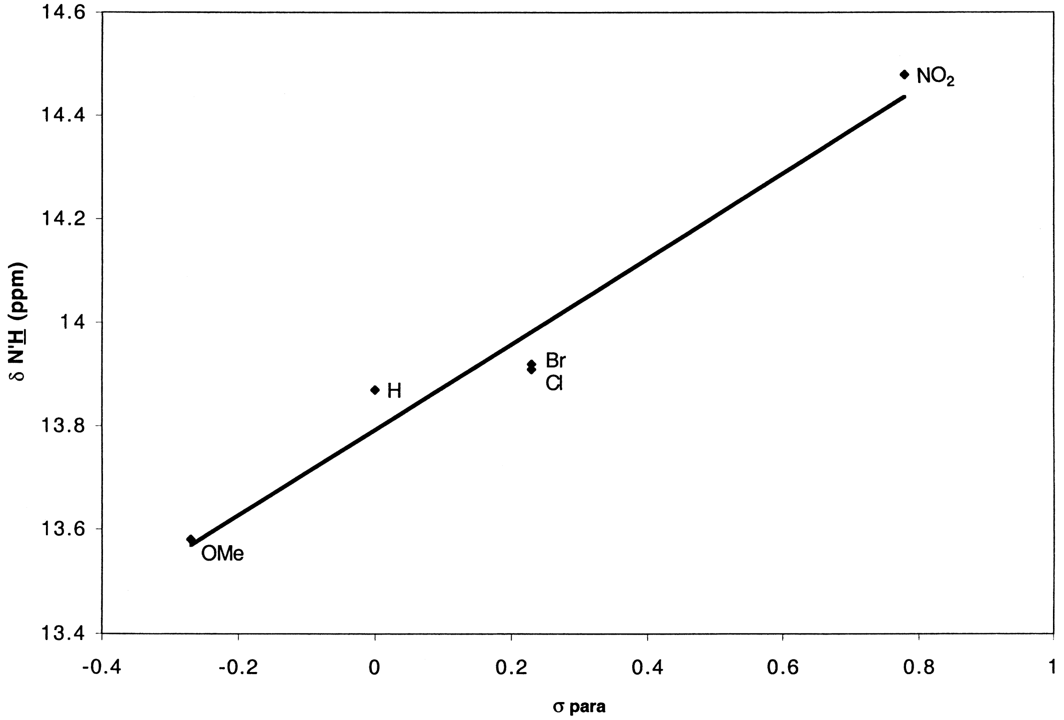

Fig. 6. Plot of the chemical shift of the N′*H* resonance vs the Hammett substituent constant for the series of PyTu4X (where X = OMe, H, Cl, Br, NO_2).

the thiourea moiety is also consistent with the formation of the intramolecular hydrogen bond. This hydrogen also interacts weakly with oxygens in PyTu4OMe and PyTu4NO_2. For PyTu4OMe the interaction is between crystallographically different molecules and the N···O average non-bonding distance is approximately 3.7 Å indicating this interaction to be considerably weaker than the intramolecular N′–H···N hydrogen bonding. Neither the chlorine or bromine atoms in PyTu4Cl and PyTu4Br form a significant interaction with the H atom involved in the intramolecular bond of the neighboring molecule.

A more important intermolecular hydrogen bonding interaction is between the thione sulfurs and N12H12 (N22H22) of neighboring molecules. The previously studied *N*-substituted and *N*,*N*′-substituted thioureas (i.e. thioureas without intramolecular hydrogen bonding) have an average N···S non-bonding distance of 3.46 Å [10–14], the smallest being 3.363(2) Å for *N*,*N*-diethyl-*N*′-(2-tolyl)thiourea [12] and the largest 3.653(1) Å for *N*-cyclohexyl-*N*′-(cyclohexyl)thiourea [11]. The *N*-(2-pyridyl)-*N*′-(tolyl)thioureas, PyTu2T (*N*-(2-pyridyl)-*N*′-(2-tolyl) thiourea), PyTu3T (*N*-(2-pyridyl)-*N*′-(3-tolyl) thiourea) and PyTu4T [16], have N···S non-bonding distances of 3.401(2), 3.387 and 3.410(2), and 3.352(4) and 3.523(4) Å, respectively, which are comparable to the thioureas of this study, Table 5. Other parameters of the N–H···S hydrogen bonding shown in Table 5 are comparable to thioureas previously studied [10–14,16]. The N–H···S hydrogen bonding interaction in the previously studied complexes results in the formation of dimers, which are often centrosymmetric [1]. When there are two or more crystallographic unique molecules, and the N–H···S interactions to form dimers are between unlike molecules, centrosymmetry is lost. Inspection of Table 5 shows that PyTu4OMe, PyTu4Cl and PyTu4Br have different interaction distances and angles for the two hydrogen bonds making up the dimer. In addition to the N–H···S hydrogen bond, the sulfur is also interacting with a pyridine hydrogen, C3H3 in PyTu4Br, but not in the other three molecules. This intermolecular hydrogen bonding interaction results in the sulfur appearing to be positioned between the two interacting molecules and is similar to the *N*-(2-pyridyl)-*N*′-(tolyl)thioureas, PyTu2T, PyTu3T and PyTu4T [16].

3.2. Spectral studies

The ^{1}H NMR spectral data (provided in Section 2) contains chemical shift evidence that the intramolecular hydrogen bonds observed in the reported solid state structures are maintained in DMSO solution (at room temperature). In general, intramolecular hydrogen bonding interactions are known to cause downfield shifts in proton resonances. For example, the previously reported *N*-(2-pyridyl)thioureas display the non-hydrogen bonded (NH) resonance around 9–10 ppm, and the intramolecularly hydrogen bonded (N′H) resonance between 12–14 ppm [2]. In addition, other organic and inorganic compounds with intramolecular hydrogen bonding show similar shifts [23,24]. By analogy, we have assigned the downfield shifts of the *N*-(2-pyridyl)-*N*′-(4-substituted phenyl)thioureas to the N*H* resonance (10.8–11.2 ppm) and the N′*H*···N resonance (13.5–14.5 ppm).

In addition to the downfield shift due to intramolecular hydrogen bonding, a number of resonances are influenced by the para substituent on the phenyl ring. For example, the phenyl ring protons, N′*H* and even the more distant N*H* are shifted downfield as the para substituents become more electron withdrawing (i.e. from –OMe, to –NO_2). To demonstrate this electronic effect the N′*H* resonances were plotted vs the Hammett parameters of the corresponding para substituents (Fig. 6). The slope of the line is positive ($R^2 = 0.960$, slope = 0.83, intercept = 13.79), consistent with the deshielding effects of electron withdrawing substituents.

4. Supplementary material

Crystallographic data (excluding structure factors) for the structures reported in this paper have been deposited with the Cambridge Crystallographic Data Center as supplementary publication no. CCDC-144804 for PyTu4OMe, CCDC-144805 for PyTu4NO_2, CCDC-144802 for PyTu4Cl and CCDC-144803 for PyTu4Br. Copies of available material can be obtained, free of charge, on application to the Director, CCDC, 12 Union Road, Cambridge CB21EZ, UK, (fax: +44-(0) 1223-336033 or e-mail: deposit@ccdc.cam.ac.uk).

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