An *X*-Ray Crystallographic, ^{1}H Nuclear Magnetic Resonance, and MNDO SCF-MO Conformational Study of *o*-Substituted *N*-Benzylbenzothiohydroxamic Acids

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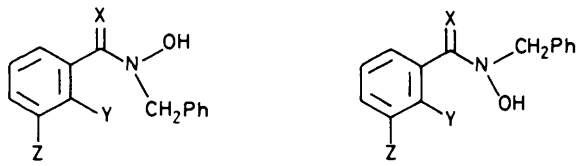
An *X*-ray determination of the structure of *N*-benzyl-*o*-methoxybenzothiohydroxamic acid (**1a**) shows the compound to have the *Z*-configuration with an intramolecular OH ··· S hydrogen bond [2.822(3) Å]. The nitrogen centre is planar, and the *C*-aryl group is orthogonal to the CNOH plane. ^{1}H and ^{13}C n.m.r. studies suggest that in non-polar solvents *o*-substituted *N*-benzylbenzothiohydroxamic acids retain the *Z*-configuration, whereas in polar solvents such as dimethyl sulphoxide or methanol the *E*-isomer is also present. The activation parameters for rotation about the aryl to (thio)carbonyl C–C single bond have been measured by a variable-temperature lineshape analysis of the ^{1}H AB quartets due to the diastereoisotopic *N*-benzylic methylene protons. The results are compared with those of MNDO SCF-MO calculations.

Previous ^{1}H n.m.r. studies of thiohydroxamic acids have shown them to exist as an equilibrium mixture of *E* and *Z* forms in solution.[1] In continuing our studies of *N*-benzylbenzothiohydroxamic acids, those with an *ortho*-substituent on the *C*-aryl group attracted our attention, since the geminal methylene protons in the ^{1}H n.m.r. spectra were magnetically non-equivalent. Such behaviour has been previously observed in *N*-benzyl-*o*-chloro-benzamides and -thiobenzamides[2a] and *NN*-dialkylbenzamides[2b] and is thought to arise from the chiral environment created by restricted rotation about the *o*-substituted aryl to carbonyl or thiocarbonyl single bond[3a] rather than to any conformational preference of the *N*-benzyl group.[3b] The conformational and structural properties of benzothiohydroxamic acids have not previously been reported. We give here details of a ^{1}H n.m.r. and *X*-ray study of these compounds and a MNDO[4] SCF-MO theoretical study of the rotational barrier about the aryl to (thio)carbonyl bond.



(1a) X = S, Y = OMe, Z = H (1b)
(2a) X = S, Y = Br, Z = H (2b)
(3a) X = O, Y = OMe, Z = H (3b)
(4a) X = S, Y = H, Z = OMe (4b)

Results and Discussion

N-Benzyl-o-methoxybenzothiohydroxamic Acid (**1**).—*Crystallographic analysis.* The structure (Figure 1) shows the thiohydroxamide configuration to be *Z* [*e.g.* (**1a**)] with an intramolecular hydrogen bond [2.822(3) Å] between the sulphur and the hydroxy group [S ··· H–O angle 131(2)°]. This group is essentially planar with a maximum deviation from the least-squares plane [comprising S(1), C(2), N(3), O(4), C(5), and C(12)] of 0.028 Å. The departure from planarity is due to a small (2°) torsional rotation about the C–N bond of the plane comprising N(3)O(4)C(5) with respect to that of S(1)C(2)C(12). The methoxyphenyl group is approximately normal to the plane of the thiohydroxamide (83° between mean planes). Inspection of the space-filling drawings (Figures 2a, b) shows rotation about the *C*-aryl bond [C(2)–C(12)] to be hindered. This is due to steric interactions between the *ortho*-methoxy oxygen atom [O(18)] and the sulphur of the thiocarbonyl in one direction and the methylene group [C(5)] in the other. The structure is loosely packed with no intermolecular contacts of less than 3.5 Å. The closest contact of note is between sulphur atoms (3.61 Å) across one of the centres of symmetry.

^{1}H *and* ^{13}C *n.m.r. analysis.* At room temperature and in $CDCl_3$ solution, the ^{1}H n.m.r. spectrum of (**1**) (see Table 1)

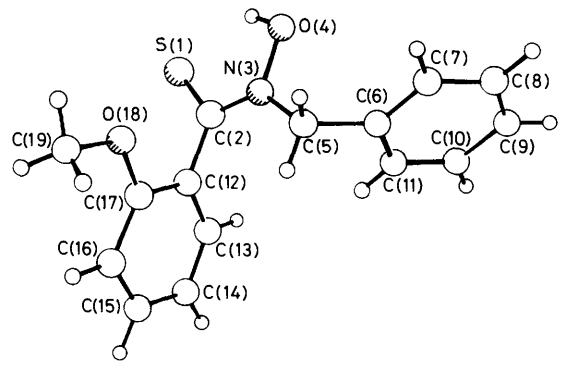


Figure 1. The molecular structure of (**1a**)

shows an AB quartet for the two benzylic protons. We interpret this in terms of restricted rotation about the aryl to thiocarbonyl bond (caused by steric interactions with the *ortho*-substituents, *e.g.* Figure 2) creating the asymmetric environment for the benzylic protons. This interpretation is supported by a number of other observations. (*i*) The ^{1}H spectrum of the *meta*-methoxy isomer (**4**) shows no diastereoisotopic behaviour for the benzylic protons even at 200 K. Although this could be the result of chemical shift equivalence of the two protons, we feel it more probable that this is due to reduced steric interactions leading to a significantly lower rotational barrier.' (ii) *N*-Isopropyl-*o*-

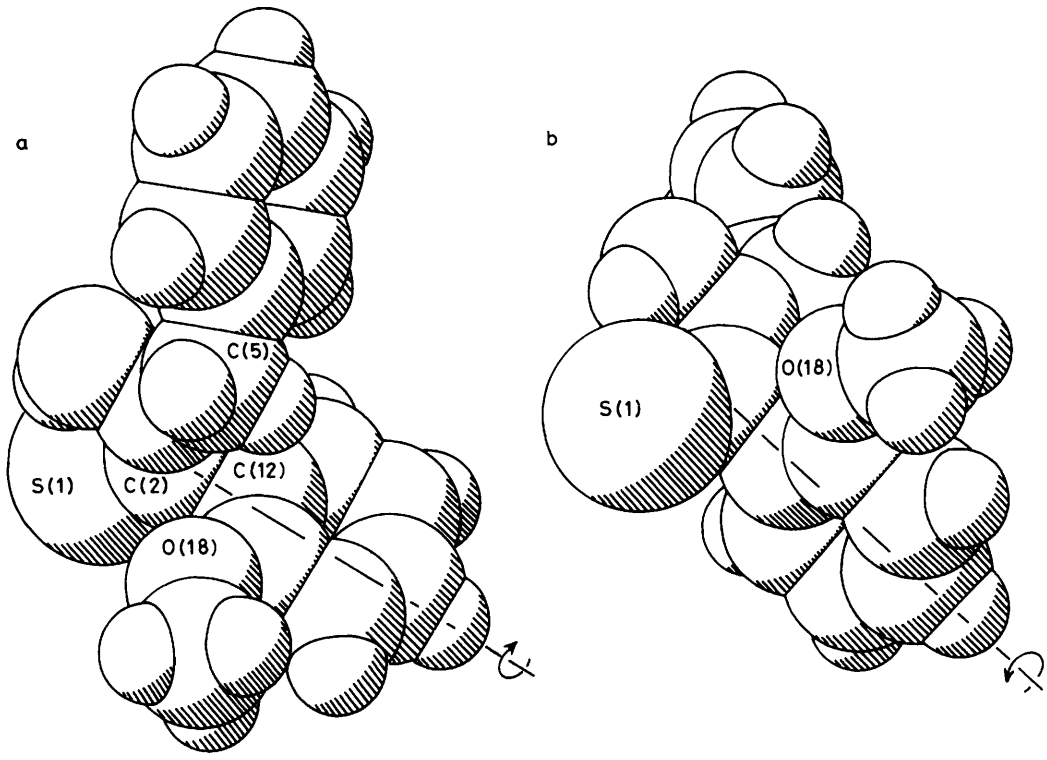


Figure 2. Space-filling representation of (**1a**) showing the hindrance to rotation about the *C*-aryl bond, C(2)–C(12) due to steric interactions between the methoxy oxygen O(18) and a, the methylene group C(5) and b, the sulphur S(1) of the thiocarbonyl group

Table 1. ^{1}H N.m.r. data for the benzylic methylene region of *o*-substituted *N*-benzylbenzo(thio)hydroxamic acids, at 300 ± 3 K

Compound	Solvent	δ_{AB} (p.p.m.)	$\Delta\delta_{AB}$ (p.p.m.)	J_{AB}/Hz	Isomer (%)
(**1a**)	$CDCl_3$	4.87 (q)	0.067	−15.2	100
(**1a**)	DMSO	4.70 (q)	0.065	−15.5	38
(**1b**)	DMSO	5.53 (q)	0.336	−15.3	62
(**2a**)	$CDCl_3$	4.85 (s)			100
(**2a**)	DMSO	4.75 (s)			37
(**2b**)	DMSO	5.47 (q)	0.118	−14.9	63
(**3a**)	$CDCl_3$	4.67 (s)			100
(**3a**)	CD_3OD	4.55 (s)			56
(**3b**)	CD_3OD	4.94 (s)			44
(**4a**)	CD_3OD	4.96 (s)			73
(**4b**)	CD_3OD	5.55 (s)			27

methoxybenzothiohydroxamic acid shows diastereoisotopic behaviour for the isopropyl group with the coalescence temperature for the corresponding ^{1}H multiplet (*ca.* 380 K) being similar to that observed for (**1**) (*ca.* 360 K). This suggests that conformational preferences of the *N*-alkyl group are unlikely to be the cause of this effect. (iii) The carbonyl analogue (**3**) shows diastereoisotopic behaviour for the benzylic proton resonances only at much lower temperatures (< 240 K), presumably since the smaller size of the oxygen atom results in a lower rotational barrier.

In polar solvents ([$^2H_6$]DMSO or CD_3OD), the ^{1}H n.m.r. spectrum of (**1**) shows an additional AB quartet to low field of the first, the total integration corresponding to two protons (Table 1). The ^{13}C spectrum in [$^2H_6$]DMSO shows 25 resonances, with one accidental degeneracy. A number of these peaks occur in pairs, which indicates the presence in solution of two very similar species. Two low-field resonances were observed at δ_C 181 and 190 p.p.m. and are assigned to the thiocarbonyl group, whilst only one such resonance (at δ_C 179 p.p.m.) was observed in $CDCl_3$. These facts tend to suggest that these two species are *E*- and *Z*-isomers. Comparison of the spectrum in [$^2H_6$]DMSO with that in $CDCl_3$, and with the observed structure in the solid state suggests, that the high-field AB quartet in [$^2H_6$]DMSO is due to the intramolecularly hydrogen-bonded *Z*-isomer (**1a**) and that the low-field AB quartet is due to the intermolecularly hydrogen-bonded *E*-isomer (**1b**) which has been stabilised by the polar solvent. The relative chemical shifts of the two quartets agree with this assignment, that due to the *Z*-isomer being shifted *upfield* as a result of shielding from the face of the orthogonal *C*-aryl group. Curiously, the low-field quartet due to the *E*-isomer shows a larger chemical shift difference between the diastereoisotopic protons ($\Delta\delta_{AB}$ 0.336 p.p.m.) than the high-field quartet due to the *Z*-isomer ($\Delta\delta_{AB}$ 0.065 p.p.m.), even though these protons in the latter isomer are physically closer to the chiral centre created by restricted rotation of the aryl group (*cf.* Figure 1). Our assignments of the *Z*- and *E*-methylene group resonances agree with those previously made for *NN*-dialkylthiobenzamides,[5] but our observation that the *E*-methylene protons experience the greater chemical shift difference is inconsistent with the reported results of Berg and Sandstrom[2] for thiobenzamides, who claim this for the *Z*-group.

We attempted to confirm these solution assignments using ^{1}H nuclear Overhauser effect difference spectroscopy (NOEDS).[6] Pre-irradiation of each of the quartets due to the benzylic CH_2 protons showed a significant n.O.e. only to the *ortho*-protons of the benzyl group (Figure 3b, c) and there was no significant difference in the enhancements of the methoxy resonances due to (**1a** and **b**). Pre-irradiation of the latter resonances (accidentially degenerate in [$^2H_6$]DMSO) showed

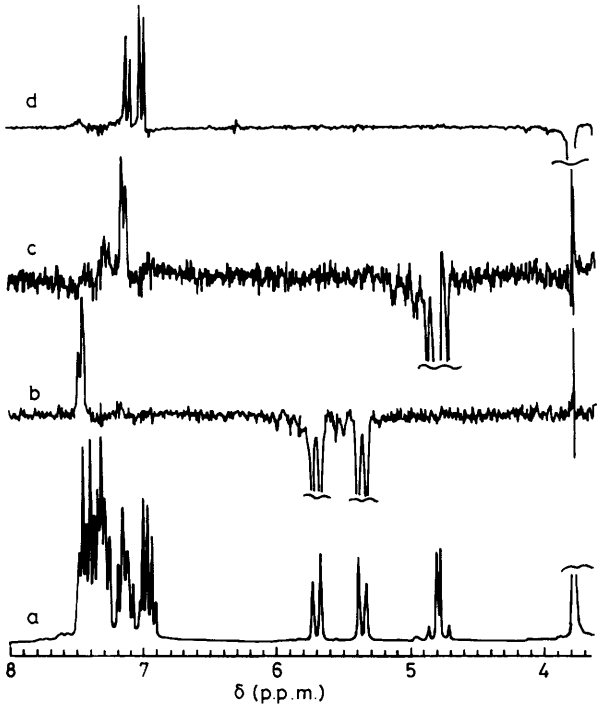


Figure 3. a, ^{1}H Spectrum of (**1**) in [$^2H_6$]DMSO at 300 K; b. n.O.e. difference spectrum obtained by ^{1}H pre-irradiation of the quartet at δ 5.53 and subtraction of the appropriate control spectrum; c. n.O.e. difference spectrum obtained by ^{1}H pre-irradiation of the quartet at δ 4.70; d, n.O.e. difference spectrum obtained by ^{1}H pre-irradiation of the methoxy resonance

again only enhancement of the proton *ortho* to the methoxy and no enhancement of either of the two benzylic CH_2 resonances (Figure 3d). The methoxy protons are therefore not significantly relaxed *via* the benzylic protons (and *vice versa*) in either the *E*- or the *Z*-isomer of (**1**), which is consistent with (but of course does not prove) our assumption that the *C*-aryl group is orthogonal to the plane of the hydroxamic acid in solution as well as in the solid state. The spectra shown in Figure 3 do strikingly illustrate the ability of the NOEDS technique to simplify complex spectral regions by selectively enhancing peaks due to specific protons.[6b]

A variable-temperature experiment in [$^2H_6$]DMSO shows that the highfield ^{1}H AB quartet coalesces to a singlet at *ca.* 355 K and the lowfield quartet coalesces at *ca.* 365 K (Figure 4). Further broadening of these two singlets due to *E*–*Z* isomerisation was not observed up to 400 K, which is consistent with the large barriers that have been observed for this process in thioamides.[7] The barriers to rotation about the aryl to thiocarbonyl single bond in both the (**1a**) and the (**1b**) isomers were obtained by a lineshape analysis of the two AB quartets as a function of temperature (Figure 4). Since effects due to exchange between the two AB systems were *not* observed at the temperatures of the experiments, each has been treated as an isolated two-spin system. The derived first-order rate constants for the exchange process (Table 2) were subjected to a suitably weighted least-squares analysis *via* the Eyring equation and the resultant activation parameters together with their standard errors are shown in Table 4. Although individual values of $\Delta H^{\neq}$ and $\Delta S^{\neq}$ determined by this procedure are well known to be prone to systematic errors,[8] comparisons between (**1a**) and (**1b**) are likely to be more reliable since the activation parameters were measured for the same solution at the same temperatures. These rotational barriers are very similar to those previously found for *o*-chlorothiobenzamides.[2]

Table 2. First-order rate constants for AB spin exchange of the *N*-benzylic CH_2 group in (**1**). T_2 0.185 s

	(**1a**)		(**1b**)	
T/K	k/s^{-1}	$\Delta\nu_{AB}$/Hz	k/s^{-1}	$\Delta\nu_{AB}$/Hz
322.0	3.1	13.2		
331.5	6.4	11.9	19.3	86.0
341.0	13.0	11.0	46.0	86.4
345.8	17.6	10.0	64.0	86.6
350.5	25.1	9.5	94.0	86.7
355.3	34.0	9.0	132.0	86.9
360.0			182.0	87.0
364.8	56.0	8.6	260.0	87.1
374.3			470.0	87.4
383.8			800.0	87.7

Table 3. First-order rate constants for AB spin exchange of the *N*-benzylic CH_2 group in (**2b**). T_2 0.085 s

T/K	k/s^{-1}	$\Delta\nu_{AB}$/Hz
364.8	8.5	20.3
370.7	11.5	19.8
374.3	14.5	19.2
380.2	20.0	18.6
383.8	24.9	18.0
389.1	32.0	17.4

Table 4. Activation parameters for AB spin exchange in *o*-substituted *N*-benzylbenzo(thio)hydroxamic acids

Compound	T_c/K [a]	$\Delta H^{\neq}$/ kJ mol^{-1}	$\Delta S^{\neq}$/ kJ mol^{-1}	$\Delta G^{\neq}$/ kJ mol^{-1}
(**1a**)	355.3	64.1 ± 3.0 [b]	−37.0 ± 1.0	75.1 ± 2.7
(**1b**)	364.8	72.2 ± 2.9	−2.9 ± 1.0	73.0 ± 2.6
(**2b**)	394.5	62.4 ± 3.0	−57.9 ± 1.1	79.6 ± 2.6
(**3a**)	240.1			54.3

[a] Approximate coalescence temperature. [b] Standard errors (68% confidence limit).

N-*Benzyl*-o-*bromobenzothiohydroxamic Acid* (**2**).—Only one signal is observed in $CDCl_3$ for the benzylic methylene protons and is assigned to the *Z*-isomer (**2a**); an additional low-field signal in [$^2H_6$]DMSO was attributed to the *E*-isomer (**2b**) (Table 1). In both solvents the peak assigned to (**2a**) is a singlet, compared with a quartet observed for (**1a**), and likewise the chemical shift difference for the benzylic AB quartet due to (**2b**) ($\Delta\delta_{AB}$ 0.118 p.p.m.) is much smaller than was observed for (**1b**). The quartet due to (**2b**) also shows a higher coalescence temperature than was observed for (**1b**) (Table 4). The rate constants obtained from spectral simulation are given in Table 3 and the derived activation parameters in Table 4.

N-*Benzyl*-o-*methoxybenzohydroxamic Acid* (**3**).—The room temperature spectrum of (**3**) in $CDCl_3$ shows only one singlet corresponding to the benzylic protons (Table 1). In polar solvents ([$^2H_6$]DMSO or CD_3OD) a second singlet appears to low-field of the first, the total integration corresponding to two protons. At *ca.* 240 K in CD_3OD, the *highfield* singlet is split into a doublet and at lower temperatures an AB quartet becomes evident ($\Delta\delta_{AB}$ 0.0456 p.p.m., J_{AB} −16.0 Hz). By analogy with (**1**), this highfield signal can be assigned to the *Z*-isomer (**3a**). A striking difference between the oxygen and sulphur isomers is that the benzylic resonance in (**3a**) shows a greater asymmetric environment than that for (**3b**), whereas the opposite was true for (**1a** and **b**). The small chemical shift

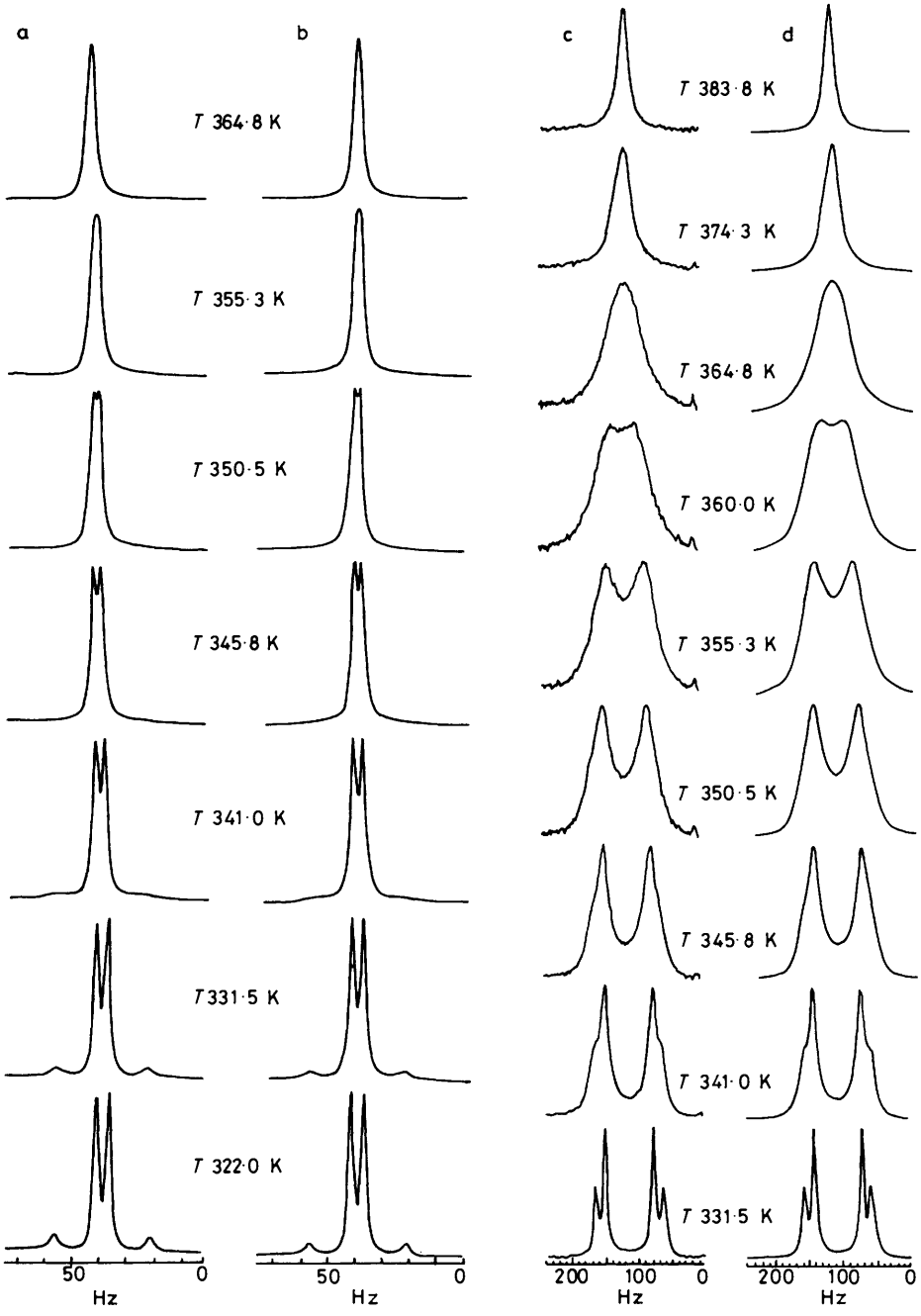


Figure 4. a, Observed and b, calculated variable-temperature ^1H spectra for the highfield quartet due to (**1a**) and c, observed and d, calculated spectra for the lowfield quartet due to (**1b**) in [$^2H_6$]DMSO

difference between the diastereoisotopic protons meant that values of the rate constant for spin exchange could not be obtained with sufficient accuracy for analysis in terms of $\Delta H^{\neq}$ and $\Delta S^{\neq}$. Nevertheless the approximate value of $\Delta G^{\neq}$ obtained by such an analysis (Table 4) is significantly lower for (**3**) than for (**1**). This difference between oxygen and sulphur has been noted previously in the study of benzamides and thiobenzamides.[2] In a related study of *o*-hydroxy-*NN*-dialkylbenzamides,[2b] Jennings *et al.* report values for $\Delta G^{\neq}$ of 40 kJ mol^{-1} or less for the rotational barriers about the aryl–C(O) bond, and these low values were rationalised in terms of hydrogen bonding between the *o*-hydroxy substituent and the carbonyl group.

MNDO SCF-MO Calculations.—The MNDO method correctly predicts the equilibrium conformation of (**1**) ($PhCH_2 = CH_3$) to have the *C*-aryl group orthogonal to the hydroxamic acid plane. The calculated activation enthalpies for the rotation process are similar to, although rather higher than, those observed. This may in part be due to imposing coplanarity upon the nitrogen centre and the (thio)carbonyl group during the calculations (*vide infra*). Loss of chirality in these species corresponds to a 180° rotation of the aryl group about the aryl to (thio)carbonyl C–C single bond. The MNDO calculations indicate that for the *Z*-isomer (**1a**) ($PhCH_2 = CH_3$) this is more easily accomplished by passage of the methoxy group past the thiocarbonyl group [$\Delta H^{\neq}_{calc}$ 98 (67) kJ mol^{-1}] rather than past

Table 5. Atomic co-ordinates ($\times 10^4$) and temperature factors ($Å^2 \times 10^3$) in (**1a**)

Atom	*x*	*y*	*z*	U_{eq}*
S(1)	5 686(1)	1 155(1)	−625(1)	86(1)
C(2)	7 103(3)	2 064(2)	−731(2)	56(1)
N(3)	7 869(2)	2 536(2)	58(1)	61(1)
O(4)	7 516(3)	2 245(2)	975(1)	85(1)
C(5)	9 096(3)	3 374(2)	155(2)	64(1)
C(6)	8 586(3)	4 363(2)	660(2)	56(1)
C(7)	9 278(3)	4 610(2)	1 609(2)	68(1)
C(8)	8 807(4)	5 505(2)	2 087(2)	81(1)
C(9)	7 638(4)	6 164(2)	1 620(2)	82(1)
C(10)	6 926(3)	5 930(2)	676(2)	80(1)
C(11)	7 406(3)	5 034(2)	191(2)	72(1)
C(12)	7 545(3)	2 361(2)	−1 696(2)	59(1)
C(13)	6 666(3)	3 088(2)	−2 317(2)	79(1)
C(14)	7 018(4)	3 353(3)	−3 223(2)	99(1)
C(15)	8 261(4)	2 832(3)	−3 527(2)	105(1)
C(16)	9 188(3)	2 094(3)	−2 953(2)	93(1)
C(17)	8 838(3)	1 873(2)	−2 002(2)	73(1)
O(18)	9 681(2)	1 199(2)	−1 321(2)	97(1)
C(19)	11 064(4)	700(3)	−1 563(4)	146(2)

* Equivalent isotropic *U* defined as one third of the trace of the orthogonalised U_{ij} tensor

Table 6. Bond lengths (Å) of (**1a**)

S(1)–C(2)	1.671(2)	C(2)–N(3)	1.307(3)
C(2)–C(12)	1.478(3)	N(3)–O(4)	1.385(3)
N(3)–C(5)	1.462(3)	C(5)–C(6)	1.499(3)
C(6)–C(7)	1.375(3)	C(6)–C(11)	1.380(3)
C(7)–C(8)	1.375(4)	C(8)–C(9)	1.364(4)
C(9)–C(10)	1.370(4)	C(10)–C(11)	1.384(4)
C(12)–C(13)	1.374(4)	C(12)–C(17)	1.380(4)
C(13)–C(14)	1.361(4)	C(14)–C(15)	1.361(5)
C(15)–C(16)	1.368(4)	C(16)–C(17)	1.409(4)
C(17)–O(18)	1.365(3)	O(18)–C(19)	1.416(4)

Table 7. Bond angles (°) of (**1a**)

S(1)–C(2)–N(3)	120.0(2)	S(1)–C(2)–C(12)	122.3(2)
N(3)–C(2)–C(12)	117.7(2)	C(2)–N(3)–O(4)	118.9(2)
C(2)–N(3)–C(5)	130.3(2)	O(4)–N(3)–C(5)	110.9(2)
N(3)–C(5)–C(6)	111.1(2)	C(5)–C(6)–C(7)	120.3(2)
C(5)–C(6)–C(11)	121.0(2)	C(7)–C(6)–C(11)	118.7(2)
C(6)–C(7)–C(8)	120.9(2)	C(7)–C(8)–C(9)	120.0(3)
C(8)–C(9)–C(10)	120.0(3)	C(9)–C(10)–C(11)	120.0(3)
C(6)–C(11)–C(10)	120.3(2)	C(2)–C(12)–C(13)	121.6(2)
C(2)–C(12)–C(17)	119.6(2)	C(13)–C(12)–C(17)	118.7(2)
C(12)–C(13)–C(14)	122.9(3)	C(13)–C(14)–C(15)	117.5(3)
C(14)–C(15)–C(16)	123.0(3)	C(15)–C(16)–C(17)	118.2(3)
C(12)–C(17)–C(16)	119.6(2)	C(12)–C(17)–O(18)	114.7(2)
C(16)–C(17)–O(18)	125.8(2)	C(17)–O(18)–C(19)	118.2(3)

the *N*-alkyl group [$\Delta H^{\neq}_{calc}$ 107 (95) kJ mol^{-1}], whereas in the *E*-isomer (**1b**), the process corresponds to passage of the methoxy group past the N–OH group [$\Delta H^{\neq}_{calc}$ 70 (69) kJ mol^{-1}] rather than past the thiocarbonyl group [$\Delta H^{\neq}_{calc}$ 80 (58) kJ mol^{-1}]. Figures in parentheses represent the calculated MNDO values for the corresponding carbonyl compounds. The calculated MNDO values of $\Delta H^{\neq}$ for the rotation process differ by 28 kJ mol^{-1} for the *Z*- and *E*-forms, whereas they are measured to differ by 8 kJ mol^{-1} in the opposite sense (Table 4). We interpret this to indicate that the *E*-isomer is in fact significantly solvated by DMSO, and that therefore the steric interactions for the *E*-isomer and hence the barrier to rotation are underestimated by the MNDO method, which of course does not include any solvation effects. The different measured values of $\Delta S^{\neq}$ for (**1a** and **b**) may indicate different solvation requirements for the respective transition states; that for (**1b**) is more positive (less negative) than that for (**1a**) and could mean some desolvation of the N–OH group of (**1b**) due to steric crowding in the transition state for rotation. The different values of $\Delta S^{\neq}$ could alternatively indicate fundamentally different transition states for rotation in the *E*- and *Z*-isomers, as indeed suggested by the MNDO calculations.

The measured values for $\Delta H^{\neq}$ and $\Delta S^{\neq}$ for (**2b**) seem anomalous compared with those for (**1b**). Although the steric bulk of a bromo substituent is larger than that of a methoxy group, the measured values of $\Delta H^{\neq}$ are in fact smaller for (**2b**) than for (**1b**). However, the more negative value of $\Delta S^{\neq}$ measured for (**2b**) leads to an overall greater value for $\Delta G^{\neq}$ for (**2b**) than for (**1b**). Although the individual values of $\Delta H^{\neq}$ and $\Delta S^{\neq}$ may be in error when compared with those for (**1**), the relative values of $\Delta G^{\neq}$ are probably more reliable. The value of $\Delta G^{\neq}$ for (**3a**) is significantly smaller than for the analogous thio compound (**1a**). These observations are all consistent with the interpretation that the chiral environment experienced by the CH_2 protons in these compounds is due to restricted rotation of the hindered *C*-aryl group[3a] rather than the alternative proposal of restricted rotation about the benzyl to nitrogen single bond.[3b] The relatively large rotational barrier found for both *o*-bromo and *o*-methoxy substituents and the apparently smaller such barrier with an *m*-methoxy substituent suggests that these effects are truly steric and not electronic in origin.

Experimental

Preparation of Substrates.—The thiohydroxamic acids were prepared from the corresponding hydroxamic acids using Lawesson's reagent. All the compounds were fully characterised by n.m.r. and mass spectral analysis. Full details are reported elsewhere.[9]

N.m.r. Spectroscopy.—Spectra were recorded on a Bruker WM250 spectrometer and the sample temperature calibrated using standard methanol and ethylene glycol samples together with the chemical shift data of Van Geet.[10] The lineshape analysis of the AB spin systems corresponding to the diastereoisotopic methylene protons of the *N*-benzyl group was carried out by comparison with simulated spectra produced by the program DNMR3H.[11b] The rate constant *k* for the exchange process and the spin–spin relaxation time T_2 were adjusted to produce the best visual fit. The chemical shift differences $\Delta\delta_{AB}$ in regions where exchange broadening prevented direct measurement were obtained by least-squares extrapolation from lower temperatures. The coupling constants J_{AB} were found to be temperature independent. In certain cases the spectrum was digitised and analysed using the iterative program DNMR5.[11a] Activation parameters for the AB exchange process were obtained by a suitably weighted least-squares analysis of the rate constants as a function of temperature using the Eyring equation.[8] Nuclear Overhauser effect difference spectra were obtained as previously described,[6a] with the modification[6b] that ^{1}H pre-irradiation of each component of the AB quartets was carried out separately. The four sets of data so obtained were then summed and from this was subtracted a multiple of four times the data acquired with the ^{1}H pre-irradiation frequency off-resonance. Nulling of unaffected peaks was essentially complete, with the exception of the methoxy resonances which showed some dispersion behaviour due to instrumental factors.

Crystal Data.—$C_{15}H_{15}NO_2S$, monoclinic, a = 8.534(1), b = 12.321(2), c = 13.704(2) Å, β = 99.12(1)°, U = 1 423 Å^3, space

group $P2_1/n$, $Z = 4$, $M = 273.4$, $D_c = 1.28\ g\ cm^{-3}$, $\mu(Cu\text{-}K_\alpha) = 19\ cm^{-1}$. Refined unit-cell parameters were obtained by centering 18 reflections on a Nicolet R3m diffractometer; 1 781 independent reflections were measured ($\theta \leqslant 55°$) with Cu-K_α radiation (graphite monochromator) using the ω-scan measuring technique. Of these 1 614 had $|F_o| > 3\sigma|F_o|$ and were considered to be observed. The data were corrected for Lorentz and polarisation factors. No absorption correction was applied.

The structure was solved by direct methods and the non-hydrogen atoms refined anisotropically. All the hydrogen atoms were clearly located in a difference electron density map. The hydroxy hydrogen was allowed to refine isotropically. The remaining hydrogens were placed at idealised positions (C–H 0.96 Å), assigned isotropic thermal parameters, $U(H) = 1.2U_{eq}(C)$, and allowed to ride on their parent carbon atoms. Refinement was by block-cascade least-squares to $R = 0.042$, $R_w = 0.051$ [$w^{-1} = \sigma^2(F) + 0.000\,32F^2$]. Computations were carried out on an Eclipse S140 computer using the SHELXTL program system.[12]

Table 5 lists the fractional atomic co-ordinates and Tables 6 and 7 give the bond lengths and valence angles respectively. The anisotropic thermal parameters, the structure factors, and the hydrogen co-ordinates and temperature factors are available as Supplementary Publication No SUP No. 56061 (13 pp.).*

SCF-MO Calculations.—Rotational barriers about the aryl to (thio)carbonyl C–C single bond were investigated using the MNDO SCF-MO method.[4] To reduce computation time, the benzyl group was modelled by a methyl group. The standard enthalpy of formation was calculated as a function of the rotation angle about this C–C bond, initially with optimisation of all the remaining $3N - 7$ degrees of freedom. During the course of these calculations it became apparent that the MNDO method significantly underestimates the barrier to C=N rotation in amides and thioamides[13] and that the method predicted concurrent rotation about the aryl to (thio)carbonyl and the (thio)carbonyl to nitrogen bonds to occur. Since this is clearly not the case experimentally, the calculations were subsequently carried out with the restriction that the two degrees of freedom relating to the coplanarity of the five atoms comprising the (thio)carbonyl and NR_2 fragments were fixed and not optimised.

* For details of the Supplementary Publications Scheme, see Instructions for Authors (1984), *J. Chem. Soc., Perkin Trans. 2*, 1984, Issue 1.

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References

1 (*a*) W. Walter and E. Schaumann, *Liebigs Ann. Chem.*, 1971, **743**, 154; (*b*) A. M. Lobo, S. Prabhakar, and M. A. Santos, *Encontro Nacional de Quimica, Communication No. 131*, Lisbon, 1981.
2 (*a*) U. Berg and J. Sandstrom, *Tetrahedron Lett.*, 1976, 3197; (*b*) W. B. Jennings, D. Randall, and B. M. Saket, *J. Chem. Soc., Chem. Commun.*, 1982, 508.
3 (*a*) T. H. Siddall, III, E. L. Pye, and W. E. Stewart, *J. Phys. Chem.*, 1970, **74**, 594; (*b*) P. J. Kruger, A. O. Fulea, C. Fulea, and F. Cornea, *Spectrosc. Lett.*, 1975, **8**, 141; W. B. Jennings and M. S. Tolley, *Tetrahedron Lett.*, 1976, 695.
4 M. J. S. Dewar and W. Thiel, *J. Am. Chem. Soc.*, 1977, **99**, 4899, 4908; M. J. S. Dewar and M. L. McKee, *ibid.*, p. 5841; M. J. S. Dewar and H. S. Rzepa, *ibid.*, 1978, **100**, 58, 777; M. J. S. Dewar, M. L. McKee, and H. S. Rzepa, *ibid.*, p. 3607; L. P. Davis, R. M. Guidry, J. R. Williams, M. J. S. Dewar, and H. S. Rzepa, *J. Comput. Chem.*, 1981, **2**, 433; M. J. S. Dewar and H. S. Rzepa, *ibid.*, 1983, **4**, 158; M. J. S. Dewar and M. L. McKee, *ibid.*, p. 82.
5 M. Frucht, A. H. Lewin, and F. A. Bovey, *Tetrahedron Lett.*, 1970, 3707.
6 (*a*) L. D. Hall and J. K. M. Sanders, *J. Am. Chem. Soc.*, 1980, **102**, 5703; (*b*) D. N. Neuhaus, *J. Magn. Reson.*, 1983, **53**, 109.
7 E. Schaumann, *Angew. Chem., Int. Ed. Engl.*, 1974, **13**, 350.
8 *Cf.* G. Binsch in 'Dynamic Nuclear Magnetic Resonance Spectroscopy,' eds. L. M. Jackman and F. A. Cotton, Academic Press, London, 1975, ch. 3, p. 70; G. Binsch and H. Kessler, *Angew. Chem., Int. Ed. Engl.*, 1980, **19**, 411.
9 A. M. Lobo, S. Prabhakar, H. S. Rzepa, and M. A. Santos, *Synthesis*, in the press.
10 A. L. Van Geet, *Anal. Chem.*, 1968, **40**, 2227.
11 (*a*) G. Stevenson and G. Binsch, Quantum Chemistry Program Exchange, Program No. 365; (*b*) *ibid.*, Program No. 458.
12 G. M. Sheldrick, SHELXTL, 'An Integrated System for Solving, Refining and Displaying Crystal Structures from Diffraction Data,' University of Gottingen, 1978.
13 H. S. Rzepa and M. A. Santos, unpublished calculations.

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