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Theoretical studies on the S—N interaction in sulfinamides

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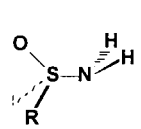
ABSTRACT: The potential energy surface of sulfinamide H(O)S—NH_2 (**1**) was searched, using *ab initio* and density functional methods, to study the conformational preferences. High-accuracy G2MP2 calculations showed that the S—N rotational barrier in **1** is 7.0 kcal mol^{-1}. The inversion around N in **1** goes through a very low energy barrier. Charge analysis using the NPA method was performed to elucidate the electronic factors responsible for the observed trends in the S—N interactions. The strength of negative hyperconjugation in **1** was estimated using NBO analysis and by studying the substituent effect. The repulsions between the lone pairs on oxygen and nitrogen and the $n_N \rightarrow \sigma^*_{S—O}$ negative hyperconjugation play an important role in the conformations. Copyright © 2002 John Wiley & Sons, Ltd.

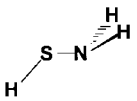
KEYWORDS: sulfinamides; S—N interaction; rotational barrier; conformation

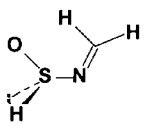
INTRODUCTION

Sulfinamides, R(O)S—NR_2, (also known as amino hydrogen sulfoxides), are important chiral building blocks in organic synthesis. Although these compounds have been known for a long time, there is renewed interest in them owing to the recognition of their application in the asymmetric synthesis of many biologically important organic molecules. For example, the *p*-tolylsulfinamides[1] and *tert*-butanesulfinamides[2] are important in the synthesis of enantiopure sulfinimines, which are employed in the synthesis of amines,[3] α- and β-amino acids,[4,5] α- and β-aminophosphonates[6,7] and many heterocycles.[5a,8,9] *N*-Acylsulfinamides are useful as dual chiral auxiliaries and in asymmetric enolate alkylation reactions.[10] Sulfinamide-based transition state isosteres, i.e. peptidosulfinamides, have applications in the development of HIV protease inhibitors.[11] Oxidation of sulfinamides using singlet oxygen yields sulfonamides, which have a wide variety of applications in medicinal chemistry.[12] Cyclic sulfinamides such as *N*-sulfinyloxazolidinones[13] and *N*-(*p*-toluenesulfinyl)aziridines[14] are important in the highly stereoselective asymmetric synthesis of several chiral organic compounds.

The S—N rotational barrier has been reported to be very high, about 12–22 kcal mol^{-1} (1 kcal = 4.184 kJ) [from the studies on sulfenamides (RS—NR_2)][15] and about 10 kcal mol^{-1} [from the studies on sulfinimine, H(O)SN=CH_2].[16] In fact, enantiomeric separation of sulfenamides can be achieved because of axial chirality along the S—N bond,[17] which has been attributed to negative hyperconjugative interactions. However, in sulfinamides, R(O)S—NR_2, no such axial chirality has been reported or any S—N rotation barrier experimentally observed. Detailed theoretical studies describing the electronic structure of the sulfinamide group and quantitative estimates of S—N bond rotations in these systems are not available. Earlier theoretical studies on sulfinamide, **1**, were limited only to geometry predictions.[18] Our studies on sulfinimines indicated that the S—N bond rotational process is influenced equally by negative hyperconjugation and electrostatic repulsions.[16a,b] In this work, we explored the electronic structure of sulfinamides, estimating the S—N rotation barriers and charge delocalizations in sulfinamides, and compared them with those of sulfenamides and sulfinimines.







1, R = H 2, R = CH_3 **5** **6**

3, R = Cl 4, R = F

METHODS OF CALCULATION

Ab initio MO[19] and density functional theory (DFT)[20] calculations were carried out using the Gaussian 94W[21] package, the Windows version of the Gaussian 94 suite of programs. Complete optimizations were performed on sulfinamide, **1**, its rotational and *N*-inversion conformers (**1-r**) and corresponding transition states (**1-rts1**, **1-rts2** and **1-its**) using the HF/6–31 + G* basis set. Since these molecules possess several lone pairs of electrons,

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Table 1. Important geometric parameters (bond lengths in Å and angles in degrees) of $H(O)SNH_2$, **1**, and its S—N rotational and N-inversion transition states obtained at the HF/6–31 + G*, MP2(full)/6–31 + G* and B3LYP/6–31 + G* levels

	HF/6–31 + G*					MP2(full)/6–31 + G*			B3LYP/6–31 + G*		
Parameter	**1**	**1-r**	**1-rts1**	**1-rts2**	**1-its**	**1**	**1-rts1**	**1-rts2**	**1**	**1-rts1**	**1-rts2**
S—N	1.677	1.665	1.702	1.705	1.654	1.708	1.743	1.740	1.728	1.771	1.762
S—O	1.472	1.469	1.464	1.473	1.469	1.504	1.499	1.503	1.505	1.500	1.504
S—H	1.337	1.344	1.342	1.348	1.342	1.365	1.371	1.381	1.379	1.386	1.398
N—H	1.004	1.000	1.002	1.005	0.998	1.022	1.023	1.024	1.022	1.023	1.023
N—H	1.001	0.999	1.004	1.002	0.996	1.019	1.025	1.021	1.019	1.025	1.021
N—S—O	112.0	108.4	107.7	106.6	109.9	114.1	105.8	106.6	114.0	105.8	106.8
N—S—H	92.2	98.1	91.0	95.6	97.2	89.3	90.1	94.8	89.3	90.2	94.9
S—N—H	112.7	117.4	110.6	107.7	120.6	113.0	106.4	106.2	112.3	105.8	106.0
S—N—H	111.2	115.2	112.6	113.8	117.4	110.6	110.3	113.1	109.9	109.5	112.4
H—S—N—O	108.0	108.1	108.8	108.8	108.0	107.9	108.9	109.1	107.6	108.4	108.9
H—N—S—O	84.0	297.7	83.1	1.0	−62.9	79.1	57.2	−5.8	78.7	56.2	−6.3
H—N—S—O	320.0	158.6	205.8	239.8	143.1	316.3	173.8	235.2	317.2	171.5	235.6
Sum of angles around nitrogen	333.3	347.0	332.6	330.6	354.8	332.8	331.2	357.9	331.3	322.5	326.6

inclusion of diffuse functions in the basis set is important. To study the effect of electron correlation on the geometries and energies, full optimizations were performed using the MP2/6–31 + G*,[22] MP2(full)/6–31 + G*,[23] B3LYP/6–31 + G*[24] and B3PW91/6–31 + G*[25] levels. Frequencies were computed analytically for all optimized species at the HF/6–31 + G*, MP2/6–31 + G*, B3LYP/6–31 + G* and B3PW91/6–31 + G* levels in order to characterize each stationary point as a minimum or a transition state and to determine the zero point vibrational energies (ZPE). The ZPE values obtained at the HF/6–31 + G* level were scaled by a factor of 0.9135[26] and at the correlated levels by a factor of 0.9656. The final values of S—N rotational barriers were estimated using the G2MP2[27] method. Atomic charges in all the structures were obtained using the natural population analysis (NPA) method within the natural bond orbital (NBO) approach[28] with the MP2 densities using the MP2(full)/6–31 + G* wavefunction. Substituent effects on the S—N interaction were studied using the MP2(full)/6–31 + G* level on X(O)S—NH_2 (X = Me, Cl, F). MP2(full)/6–31 + G* geometric parameters and G2MP2 energies will be used in the discussion unless specifically mentioned otherwise. The generalized anomeric interactions observed in sulfonamides **1**–**4** and sulfinimines **6** are similar to the generalized anomeric interactions reported across P—N and P—C(—) axes in phosphondiamides and related systems.[29] In both S—N and P—N rotational processes the preferred conformations are those which maximize hyperconjugative stabilizations and minimize lone pair–lone pair repulsions.

RESULTS AND DISCUSSION

On the potential energy surface of sulfinamide $H(O)SNH_2$, two minima, **1** and **1-r**, two rotational transition states, **1-rts1** and **1-rts2**, and one inversion transition state, **1-its**, could be located at the HF/6–31 + G* level. At the HF/6–31G*, MP2/6–31 + G*, MP2(full)/6–31 + G*, B3LYP/6–31 + G* and B3PW91/6–31 + G* levels only one minimum (**1**) and two rotational transition states (**1-rts1** and **1-rts2**) were found. Because of the small inversion barrier, **1-r** is converted into **1** through an inversion process at these levels. The geometrical data corresponding to these structures are given in Table 1.

The S—N bond length in **1** is 1.677 Å at the HF/6–31 + G* level, which is only slightly longer than that in the x-ray crystal structure of 2,2,6,6-tetradimethyl-4-oxopiperidine (1.652 Å)[30] [in 2,2,6,6-tetramethyl-4-oxopiperidine (**A**)[30a] also *N*-pyramidalization is negligible; hence it is more appropriate to compare the S—N distance in A (1.652 Å) with that in **1-its** (1.662 Å) at the HF/6–31 + G* level, and the agreement is excellent, which indicates that the HF/6–31 + G* estimates of S—N bond lengths are highly reliable]. This distance increases to 1.708 and 1.728 Å after including electron correlation at the MP2 and B3LYP levels respectively. This is consistent with the earlier observations that inclusion of electron correlation overestimates the S—X bond lengths.[16] The S—N bond length in **1** (1.677 Å) is shorter than the S—N single bond length of 1.709 Å in sulfenamide HS—NH_2 but longer than the S=N double bond length (1.537 Å) in S=NH obtained at the HF/6–31 + G* level; a similar trend is observed at the MP2 and B3LYP levels also. This leads to the conclusion that there is partial double bond character in sulfinamides. The shorter S—N bond length has been attributed to N lone pair delocalization into the sulfur d-orbital. However, Reed and Schleyer showed that sulfur d-orbital participation is negligible even in hypervalent sulfur compounds.[31] The smaller S—N distance may be attributed

Table 2. Absolute energies (in a.u.) and zero point vibrational energies (ZPE) (in kcal mol^{-1}) of H(O)SNH$_2$ at various levels

Method	**1**	**1-r**	**1-rts1**	**1-rts2**	**1-its**
HF/6–31G*	−528.48156	–	−528.49783	−528.46743	–
HF/6–31 + G*	−528.49073	−528.48304	−528.47797	−528.47741	−528.48294
MP2/6–31 + G*	−528.97806	–	−528.96303	−528.94443	–
MP2(full)/6–31 + G*	−528.99694	–	−528.98384	−528.98188	–
B3LYP/6–31 + G*	−529.91031	–	−529.89848	−529.89647	–
B3PW91/6–31 + G*	−529.80992	–	−529.79764	−529.79551	–
G2MP2	−529.28984	–	−529.28007	−529.27865	–
ZPE (NIF)[a]	25.42 (0)	27.72 (0)	24.80 (1)	24.64 (1)	24.30 (1)[b]

[a] NIF = number of imaginary frequencies.
[b] At the HF/6–31 + G * level scaled by 0.9135.

to $n_N \rightarrow \sigma^*_{S—H,}$ $n_N \rightarrow \sigma^*_{S—O}$ negative hyperconjugative interactions or S—N electrostatic interactions. The N—S—H angle in **1** is 92.2° at the HF/6–31 + G* level, small as expected for a divalent sulfur. The NH_2 group is highly pyramidalized, as indicated by the sum of angles around nitrogen, 333.3°, 332.5° and 331.3° at the HF/6–31 + G*, MP2(full)/6–31 + G* and B3LYP/6–31 + G* levels, respectively. In the rotational transition states **1-rts1** and **1-rts2**, the S—N bond length is elongated by ∼0.03 Å at the HF/6–31 + G* level. In **1-rts1** and **1-rts2** pyramidal character has increased as expected, the sum of angles around nitrogen being 332.6° and 330.6°, respectively, at the HF/6–31 + G* level.

The absolute energies and the ZPE values of **1** and its related structures are given in Table 2 and the relative values are given in Table 3. The conformer **1-r** could not be located on the potential energy surface at the HF/6–31G*, MP2/6–31 + G*, MP2(full)/6–31 + G*, B3LYP/6–31 + G* and B3PW91/6–31 + G* levels. Complete optimization on **1-r** at all these levels using Berny and eigenvalue following (EF) algorithms resulted in **1**. Conformation **1-r** is 4.13 kcal mol^{-1} higher in energy than **1** at the HF/6–31 + G*(+ ZPE) level. The lowest energy structure **1** has a conformation in which the lone pair on nitrogen is *anti* to the S—O bond and the lone pairs on sulfur and nitrogen are *gauche* to each other (Fig. 1). This arrangement is ideal for strong $n_N \rightarrow \sigma^*_{S—O}$ anomeric interaction; this second-order interaction amounts to 12.41 kcal mol^{-1} (Table 4) with an energy difference of 1.05 kcal mol^{-1} between the interacting orbitals and Fock matrix element (which is a measure of overlap) of 0.10. In **1-r** the lone pair on nitrogen is *gauche* with respect to both S—O bond and S lone pairs such that the arrangement leads to $n_N \rightarrow \sigma^*_{S—H}$ interaction. In both **1** and **1-r**, the lone pair on S is *gauche* with respect to lone pair on N. Hence the instability of **1-r** can be attributed to the repulsion between the lone pairs on oxygen and nitrogen. Similar results have been observed in sulfinimines also.[15a] The S—N rotational process goes through the transition states **1-rts1** and **1-rts2**, with **1-rts2** having relatively higher energy at all the levels. **1-rts2** has an eclipsed arrangement of the lone pairs on S and N, whereas **1-rts1** has a *gauche* arrangement of lone pairs on N with that of S—O bond. The S—N rotational path in **1** (via **1-rts2**) goes through an energy barrier of 7.6 kcal mol^{-1} at the HF/6–31 + G*(+ZPE) level. After including the electron correlation at the MP2(full) and B3LYP levels, the S—N rotational barrier increases slightly to 8.5 and 7.8 kcal mol^{-1}, respectively. The G2MP2 estimate of the S—N rotational barrier is 7.0 kcal mol^{-1}. The S—N barrier in **1** (7.0 kcal mol^{-1}) is slightly larger than that in sulfenamide HS—NH_2, **5** (6.6 kcal mol^{-1} at G2MP2).[16c] The N-inversion barrier in **1** is 4.9 kcal mol^{-1} at the HF/6–31 + G* level. The energy barrier for the inversion in **1-r** is only 0.06 kcal mol^{-1}. After including the ZPE correction, even this small barrier disappears. At other theoretical levels, **1-r** and hence **1-its** could not be located, presumably owing to the negligible inversion barrier.

Table 3. Relative energies, rotational barriers and inversion barriers (all in kcal mol^{-1}) of H(O)SNH$_2$ at various levels[a]

Method	**1** → **1**−**r**: ΔE	**1** → **1**−**rts1**: rotational barrier	**1** → **1**−**rts2**: rotational barrier	**1** → **1**−**its**: inversion barrier
HF/6–31 G*	–	8.6 (7.9)	8.9 (8.0)	–
HF/6–31 + G*	4.8 (4.1)	8.0 (7.4)	8.4 (7.6)	4.9 (3.8)
MP2/6–31 + G*	–	9.4 (8.5)	9.4 (8.9)	–
MP2(full)/6–31 + G*	–	8.2 (7.3)	9.4 (8.5)	–
B3LYP/6–31 + G*	–	7.4 (6.7)	8.7 (7.8)	–
B3PW91/6–31 + G*	–	7.7 (6.8)	9.0 (8.3)	–
G2MP2	–	– (6.1)	– (7.0)	–

[a] ZPE corrected values are given in parenthesis.

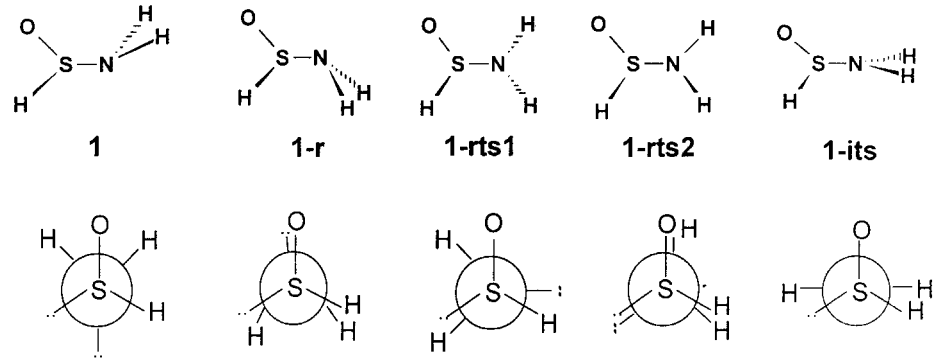

Figure 1. Structures and Newman projections of **1, 1-r, 1-rts1, 1-rts2** and **1-its**

Atomic charges obtained by using NPA method are given in Table 5. The data indicate that the N atom possesses 1.145 units of negative charge and sulfur possesses 1.312 units of positive charge. During the S—N bond rotation the atomic charges are not strongly influenced. This indicates that the strong polarization along the S—N bond, which is originated from the S—O bond polarization (S 1.312 and O − 1.061) does not become distributed during the rotation. The NBO analysis (Table 4) shows that the $n_N \rightarrow \sigma^*_{S—H}$ anomeric delocalization energy at 1.10 kcal mol^{-1} in **1** is weak. The $n_N \rightarrow \sigma^*_{S—O}$ anomeric delocalization is much stronger (12.41 kcal mol^{-1}), but upon rotation this value is reduced to 1.48 and 1.55 kcal mol^{-1} in **1-rts1** and **1-rts2**, respectively. This shows that the stabilization of **1** is mainly due to the strong $n_N \rightarrow \sigma^*_{S—O}$ delocalization and this anomeric interaction causes S—N partial double bond character. In **1**, the $n_O \rightarrow \sigma^*_{S—N}$ donation is also very strong [$E^{(2)}$ = 33.89 kcal mol^{-1}], which reduces only slightly upon S—N rotation in **1-rts1** [$E^{(2)}$ = 30.48 kcal mol^{-1}] and **1-rts2** [$E^{(2)}$ = 29.14 kcal mol^{-1}]. The $n_N \rightarrow \sigma^*_{S—O}$ interaction induces a small π character between S and N whereas the $n_O \rightarrow \sigma^*_{S—N}$ interaction reduces the σ character; these two factors oppose each other, hence the S—N bond order is not strongly affected, which is reflected in the Wiberg bond index (0.897) and AIM bond order (1.010).

Table 4. Second-order energy analysis $E^{(2)}$, energy differences ($E_j - E_i$) and Fock matrix elements associated with various anomeric interactions in sulfinamides

Structure		$E^{(2)}$ (kcal mol^{-1})	$E_j - E_i$ (a.u.)	F_{ij} (a.u.)
1	$n_N \rightarrow \sigma^*_{S–O}$	12.41	1.05	0.10
	$n_N \rightarrow \sigma^*_{S–H}$	1.10	0.90	0.03
	$n_O \rightarrow \sigma^*_{N–S}$	33.89	0.75	0.14
	$n_O \rightarrow \sigma^*_{S–H}$	10.35	0.78	0.08
1-rts1	$n_N \rightarrow \sigma^*_{S–O}$	1.48	1.08	0.04
	$n_N \rightarrow \sigma^*_{S–H}$	1.85	0.42	0.04
	$n_O \rightarrow \sigma^*_{N–S}$	30.48	0.73	0.13
	$n_O \rightarrow \sigma^*_{S–H}$	11.36	0.77	0.09
1-rts2	$n_N \rightarrow \sigma^*_{S–O}$	1.55	1.05	0.03
	$n_N \rightarrow \sigma^*_{S–H}$	2.72	0.88	0.04
	$n_O \rightarrow \sigma^*_{N–S}$	29.14	0.74	0.13
	$n_O \rightarrow \sigma^*_{S–H}$	12.81	0.76	0.09
4	$n_N \rightarrow \sigma^*_{S–O}$	11.37	1.08	0.10
	$n_N \rightarrow \sigma^*_{S–F}$	2.69	1.09	0.05
	$n_O \rightarrow \sigma^*_{N–S}$	22.65	0.93	0.13
	$n_O \rightarrow \sigma^*_{S–F}$	4.34	1.03	0.06
	$n_S \rightarrow \sigma^*_{S–F}$	1.05	1.32	0.03
4-rts1	$n_N \rightarrow \sigma^*_{S–O}$	8.75	1.07	0.04
	$n_N \rightarrow \sigma^*_{S–F}$	–	–	–
	$n_O \rightarrow \sigma^*_{N–S}$	22.47	0.92	0.03
	$n_O \rightarrow \sigma^*_{S–F}$	3.76	0.99	0.09
	$n_S \rightarrow \sigma^*_{S–F}$	0.97	1.28	0.03
4-rts2	$n_N \rightarrow \sigma^*_{S–O}$	7.21	0.99	0.08
	$n_N \rightarrow \sigma^*_{S–F}$	1.19	1.29	0.04
	$n_O \rightarrow \sigma^*_{N–S}$	22.33	0.91	0.13
	$n_O \rightarrow \sigma^*_{S–F}$	3.94	0.98	0.06

Substituent effect

To understand the substituent effect on the S—N interactions, HF/6–31 + G*, MP2/6–31 + G*, MP2

Table 5. Atomic charges (NPA) and lone pair occupation of **1-r**, **1-rts1** and **1-rts2** at MP2(full)/6–31 + G*, MP densities

	1-r	**1-rts1**	**1-rts2**
Atomic charges—			
N	−1.145	−1.127	−1.144
S	1.312	1.298	1.333
O	−1.061	−1.044	−1.052
H	0.053	0.049	0.022
H	0.419	0.420	0.429
H	0.412	0.405	0.411
Occupation—			
$\rho(n_N)$	1.953	1.986	1.982
$\rho(n_S)$	1.987	1.996	1.991
$\rho(n_O)_1$	1.995	1.997	1.996
$\rho(n_O)_2$	1.927	1.925	1.928
$\rho(n_O)_3$	1.830	1.836	1.839

Table 6. Important parameters (geometric, charges, energy, rotational barriers) of sulfinamides **1–4** at the MP2(full)/6–31 + G* level

Parameter	H (**1**)	CH_3 (**2**)	Cl (**3**)	F (**4**)
S—N	1.708	1.712	1.695	1.686[a]
S—O	1.504	1.509	1.480	1.472[a]
N—S—O	114.1	112.2	111.7	111.6[b]
N—S—X	89.3	93.8	92.0	91.1[b]
S—N rot. barrier (1)	7.30	5.88	0.85	0.40[c]
S—N rot. barrier (2)	8.53	7.35	3.07	2.70[c]
Atomic charges—				
S	1.312	1.490	1.555	1.873
N	−1.145	−1.140	−1.140	−1.150
NH_2	−0.304	−0.307	−0.278	−0.290
O	−1.061	−1.075	−0.993	−1.012
X	0.053	−0.097	−0.283	−0.571
Electron density—				
$\rho(n_N)$	1.953	1.958	1.951	1.948
$\rho(\sigma^*_{S—X})$	0.078	–	0.207	0.103
$\rho(\sigma^*_{S—O})$	0.042	0.042	0.056	0.055

[a] Bond length in Å.
[b] Angle in degrees.
[c] Energy in kcal mol^{-1}, ZPE corrected.

Table 7. Important data (geometric, charges, energy, NBO analysis) of sulfinamide **1** and sulfinimine **6** at the MP2(full)/6–31 + G* level

Parameter	**1**	**6**
S—N bond length	1.708	1.756[a]
S—O bond length	1.504	1.506[a]
O—S—N angle	114.1	112.0[b]
O—S—N-: angle	162.3	165.7[b]
S—N rotational barrier	8.53	9.88[c]
Atomic charges—		
S	1.312	1.288
N	−1.145	−0.713
O	−1.061	1.055
NBO analysis—		
$n_N \rightarrow \sigma^*_{S—O}$:		
E	12.41	6.05[c]
$E_j - E_i$	1.05	1.17[d]
F_{ij}	0.10	0.07[d]
$n_O \rightarrow \sigma^*_{S—N}$:		
E	33.89	5.12[c]
$E_j - E_i$	0.75	0.77[d]
F_{ij}	0.14	0.06[d]

[a] Bond length in Å.
[b] Angle in degrees.
[c] Energy in kcal mol^{-1}.
[d] In a.u.

(full)/6–31 + G* and B3LYP/6–31 + G* calculations on $CH_3(O)S—NH_2$ (**2**), $Cl(O)S—NH_2$ (**3**) and $F(O)S—NH_2$ (**4**) were performed. Important geometric parameters obtained at the MP2(full)/6–31 + G* level are given in Table 6. The S—N bond length in **2** (1.712 Å) is slightly longer than that in **1** (1.708Å). Methyl sulfinamide **2** shows conformational preferences similar to that in **1**. The rotamer **2-r** could be located on the S—N rotational path of **2** at all theoretical levels. The ΔE between **2** and **2-r** is about 4.33, 4.92 and 4.40 kcal mol^{-1} at the HF/6–31 + G*, MP2(full)/6–31 + G* and B3LYP/6–31 + G* levels (after including ZPE), respectively. The N-inversion barrier in **2-r** is very small, ∼0.20, 0.23 and 0.16 kcal mol^{-1}, respectively, at the same levels. However, on inclusion of ZPE correction even this small barrier disappears. This indicates that although alkyl groups attached to sulfur in sulfinamides stabilize the second ground state, the stability is very low. The S—N rotational barrier in **2** is 6.8, 7.3 and 6.4 kcal mol^{-1} at the HF/6–31 + G*, MP2(full)/6–31 + G* and B3LYP/6–31 + G* levels, respectively; these values are slightly less than the corresponding S—N rotational barriers in **1** (7.6, 8.5 and 7.8 kcal mol^{-1}). This indicates that alkyl substitution at S reduces the S—N rotational barrier in sulfinamides. Chloro (**3**) and fluoro (**4**) substituents reduce the S—N and S—O bond lengths in sulfinamides, and this reduction in the bond length can be attributed to the increased positive charge on S (Table 6). Only one ground state and two rotational transition states could be found on the potential energy surface of **3** and **4**. The S—N rotational barriers in **3** and **4** are 3.1 and 2.7 kcal mol^{-1}, respectively, at the MP2(full)/6–31 + G* level, much less than that in **1**. The reduction in the rotational barrier is due to the increase in stabilization of rotational transition states due to the increased negative hyperconjugation. Table 4 shows that the energy of the $n_N \rightarrow \sigma^*_{S—O}$ delocalization is reduced by ∼10 kcal mol^{-1} in **1** during rotation, but this interaction is reduced by only ∼2.5 kcal mol^{-1} in **4**. This analysis shows that the $n_N \rightarrow \sigma^*_{S—O}$ interaction increases in the rotational transition states and causes a reduction in the rotation barriers. This is in contrast to the substituent effect observed in sulfenamide **5**, where fluorine substitution on sulfur increases the rotational barrier by 12.2 kcal mol^{-1} at the MP2/6–31 + G* level. From the above discussion, it is clear that negative hyperconjugation plays an important role in sulfenamides and sulfinamides, but the variation of this effect as a function of substituents is opposite in these two cases: in sulfenamides the S—N bond rotational barrier increases, causing axial chirality, and in sulfinamides the S—N bond free rotation increases and axial chirality should not be expected.

One of the important derivatives of sulfinamides are sulfinimines.[1,2] The restricted rotation along the S—N bond in sulfinimines has been shown to be responsible for the facial selectivity in sulfinimines.[16] It is worthwhile comparing the strength of S—N interactions in sulfinamide **1** and sulfinimines **6**. Table 7 gives a comparison of geometric parameters, charges and NBO analysis of **1** and **6** obtained at the MP2(full)/6–31 + G* level. The S—N distance in **1** (1.708 Å) has increased to 1.756 Å in **6**, but the S—O distance and N—S—O angle do not show

any variation. The O—S—N-: torsional angle is 162.3° in **1** assuming that the lone pair bisects the H5—N—H6—O obtuse angle. The corresponding angle in **6** is 165.7°, which is comparable. This shows that in both **1** and **6** the $n_N \rightarrow \sigma^*_{S—O}$ interactions are similar. Table 7 shows that the energy of the $n_N \rightarrow \sigma^*_{S—O}$ interaction in **1** is about double that in **6**, mainly originating from the greater overlap as represented by the Fock matrix element and greater energy difference between n_N and $\sigma^*_{S—O}$ orbitals. The elongation of the S—N bond length in **6** compared with that in **1** can be mainly attributed to the decrease in the negative hyperconjugation. The S—N rotational barrier in **6** (9.9 kcal mol^{-1}) is higher than that in **1** (8.5 kcal mol^{-1}) by about 1 kcal mol^{-1}. The higher S—N rotational barrier in sulfinimines **6** in relation to sulfinamide **1**, in preference to a weaker anomeric interaction, can be attributed to the intramolecular C—H… O hydrogen bonding in **6**.

CONCLUSIONS

The S—N bond in sulfinamides is characterized by an $n_N \rightarrow \sigma^*_{S—O}$ negative hyperconjugative interaction, in addition to covalent interactions, which is responsible for the high rotation barrier in H(O)S—NH_2. However, the rotation barrier is reduced in substituted sulfinamides because substituents stabilize the rotational transition states. Electrostatic attraction between S and N rather than anomeric π character can explain the shortening of the S—N bond length in sulfinamides in relation to sulfenamides. Sulfinimines have about half the $n_N \rightarrow \sigma^*_{S—O}$ interaction relative to that in sulfinamides.

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