The Rotational Barrier About the Disulphide Bridge in Dimethyl Disulphide: An *Ab Initio* Study

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An *ab initio* molecular orbital technique was used to investigate the rotational barrier about the disulphide bridge in dimethyl disulphide. Various minimal and extended basis sets were used in the calculations. The chosen minimal basis set was the STO-3G set, and the extended basis sets were the STO 4-31G set, the Dunning and Hay set consisting of contracted Gaussian basis sets: [2s], [3s, 2p] and [6s, 4p] for H, C, and S atoms, and the Dunning and Hay basis set augmented with a *d*-type function on S atoms. The total energy was calculated as a function of the torsion angle about the disulphide bond. The barrier to rotation about this bond was found to be two-fold in nature, in accordance with previous findings. The heights of the barriers were observed to depend upon the basis set and input geometry. For our particular choice of basis sets and input geometry, the calculated value of the *cis* and *trans* barriers ranged from 12.68 to 16.49 kcal/mol and from 6.23 to 8 kcal/mol, respectively. Inclusion of a *d*-type function in the basis sets was found to result in better agreement between the calculated and experimental values, thereby emphasizing the need for considering 3*d* orbitals of sulphur in MO calculations.

Introduction

MO theory [1] has been used to investigate disulphide bridges in the simple model compounds hydrogen persulphide and dimethyl disulphide [2–17]. Studies of these compounds by both semi-empirical [2–11] and *ab initio* [12–17] techniques indicated that the rotational barrier about the disulphide bond is two-fold in nature and that, in agreement with the early theoretical predictions of Pauling [18] and later experimental determinations [19, 20], the most stable conformation corresponds to a torsion angle about this bond in the neighborhood of ±90°. Dimethyl disulphide is of particular interest because it is the simplest model compound containing the four consecutive atoms C–S–S–C, the sequence found in the disulphide bridge regions of cystine containing peptides and proteins.

Heights and shapes of rotational barriers can be calculated by MO techniques. The heights of these barriers are often exaggerated when calculated by semi-empirical methods [21, 22], but realistic values of these heights can be calculated by *ab initio* methods provided that suitable basis sets for the MO's are chosen [23].

We report here the results of an *ab initio* study of the rotational barrier about the disulphide bond [24] of dimethyl disulphide using [2s], [3s, 2p] and [6s, 4p] basis sets for the C, H, and S atoms. In one case the basis set for the S atom was augmented with a 3*d* function, i.e. for S, the contracted set [6s, 4p, 1d] was used. The results of the present study are compared with both calculated and experimental values reported in the literature [2, 7, 16, 17, 25, 26]. A previous study on dimethyl disulphide by Eslava et al. [17] used a minimal basis set, STO-3G, and an extended split-valence basis set, STO 4-31G.

Method

The HONDO MO program [27] was used to calculate the total energy E as a function of θ, the torsion angle about the disulphide bond [24]. All calculations were performed on the CDC-7600 computer at the Lawrence Berkeley Laboratory, University of California, Berkeley, CA. In our calculations we set bond lengths and bond angles at or near their experimentally determined values [19, 20], and used various basis sets [28–32], one of which [32] included a *d*-type function on each S atom. We felt that it was worthwhile to include this type of function in at least one of the basis sets since 3*d* orbitals contribute, at least to some degree, to the bonding between S atoms, i.e. to the di-

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sulphide bond [4–6, 13, 16, 33]. Geometry optimization for the size of the molecule and the basis set considered in the present study were not undertaken due to prohibitive costs.

Results and Discussion

Table 1 shows the total energy E of dimethyl disulphide calculated as a function of θ. The values of $|\theta_0|$, which correspond to the estimated minimum value of E, are only slightly larger than 84.7 ° and 83.9 °, the values determined in the microwave [19] and electron diffraction [20] studies, respectively.

Table 2 shows the values of the heights of the *cis* and *trans* rotational barrier (see [24] for the definition of *cis* and *trans* conformations) that were calculated from the data presented in Table 1, and that were reported by others [2, 7, 16, 17]. Separate values for *cis* and *trans* barriers have not been determined experimentally, although one group has reported two different values, 9.5 kcal/mol and 6.8 kcal/mol, determined from Raman [25] and thermodynamic [26] data, respectively. The former, larger value is approximately equal to the mean of *cis* and *trans* values, and the latter, smaller value was associated by the authors with a so-called effective barrier height. If the thermodynamic properties used to calculate this barrier are sensitive mainly to the more easily surmounted barrier, the effective height primarily reflects the *trans* barrier, which all calculations indicate to be lower than the *cis* barrier (e.g., see the consistency of the examples in Table 2). If so, the values calculated with the STO-3G basis set are in particularly good agreement with the experimentally determined values. Note that values calculated by semi-empirical methods appear to be either too low (PCILO method) or too high (CNDO/2 method).

The values of barrier heights calculated by us using the STO-3G and 4-31G basis sets differ slightly from those calculated by Eslava et al. [17] using the same sets (see Table 2). These apparent discrepancies reflect the different geometries (e.g., bond lengths and bond angles) used in the calculations. We used geometric input that was at or near the experimentally determined values, whereas Eslava et al. [17] used input parameters that were calculated by geometric optimization, a process in which these parameters are varied to achieve a

Table 1. Total energy (E) of dimethyl disulfide as a function of the magnitude of the torsion angle about the disulfide bond ($|\theta|$)[a].

$\lvert\theta\rvert$	E, a.u.			
	STO-3G[b]	4-31G[c]	DH[d]	DH + d[e]
0 °	−864.641718632	−873.182847647	−874.088911570	−874.176011484
80 °	−864.661682078	−873.207409837	−874.113619751	−874.202000851
82.5 °	−864.661818675	−873.207567206	−874.113820820	−874.202168661
85 °	−864.661903745	−873.207663783	−874.113965199	−874.202272431
87.5 °	[f]	−873.207703074	−874.114056053	−874.202315561
90 °	−864.661931216	−873.207688501	−874.114096411	−874.202301390
92.5 °	−864.661879297	−873.207623439	−874.114089276	−874.202233226
95 °	[f]	−873.207511097	−874.114037435	[f]
180 °	−864.651940563	−873.196212122	−874.104166947	−874.189555129
$\lvert\theta_0\rvert$[g]	88.3 °	88.2 °	90.9 °	88.2 °
E_0	−864.661944608 a. u.	−873.207705409 a. u.	−874.114102658 a. u.	−874.202319161 a. u.

[a] Values of E were calculated by the HONDO MO program [27], which made use of C_2 symmetry about the center of the S−S bond. Bond lengths (b's) and bond angles (τ's) were set at the following values, which are at or near the values determined in a microwave study [19] (cf. values determined in an electron-diffraction study [20]): b(S−S), 2.038 Å; b(C−S), 1.81 Å; b(C−H), 1.09 Å; τ(S−S−C), 103°. The methyl Cs were assumed to be tetrahedral, so that all τ's involving H−C were set at 109.47°. Both methyl groups were assumed to be staggered (i.e., the methyl Hs and their vicinal S form torsion angles of +60°, −60°, and 180°).

[b] Ref. [28]. [c] Ref. [29]. [d] Ref. [30]. [e] Ref. [32].

[f] Calculation did not converge.

[g] Values of E_0 and $|\theta_0|$ were estimated from a least-squares fit of data corresponding to values of $|\theta|$ between 80° and 95° to a quadratic equation – i.e., data were fitted to an equation of the form $E(|\theta|) = A|\theta|^2 + B|\theta| + C$; E_0, the minimum value of E, which is given by $-B/4A + C$, occurs at a value of $|\theta|$, designated by $|\theta_0|$, given by $-B/2A$.

Table 2. Calculated values of the heights of torsional barriers about the disulfide bond (ΔE)[a].

barrier[b]	ΔE, kcal/mol			
	STO-3G[c,d]	4-31G[c,d]	DH[c,d]	DH + d[c,d,e]
cis	12.68 (15.62)[f]	15.58 (18.47)[f]	15.79	16.49
trans	6.27 (5.05)[f]	7.20 (6.04)[f]	6.23	8.00
	DZ[c,h,j]	MB[c,i,j]	PCILO[g,k]	CNDO/2[g,l]
cis	16.03	13.11	2.9[m]	19.1[n]
trans	9.16	10.39[o]	1.3[p]	9.5

[a] Also see Table 1 of Pappas [16] and Table 2 of Eslava et al. [17].

[b] For heights of barriers calculated from data taken from Table 1, $\Delta E_{cis} \equiv E(0°) - E_0$ and $\Delta E_{trans} \equiv E(180°) - E_0$, where E_0 is the minimum energy at θ_0; for heights of barriers obtained from other sources, see original references for exact definitions of *cis* and *trans* barriers.

[c] *Ab initio* calculation.

[d] Values are calculated from data given in Table 1; see footnotes b–e to Table 1 for definitions of these basis sets. Bond lengths and bond angles were taken from experimentally determined values [19, 20].

[e] Basis set includes a *d* orbital function.

[f] Values within parentheses are taken from Table 1 of Eslava et al. [17], who used geometric optimization to determine bond lengths and bond angles.

[g] Semi-empirical calculation.

[h] DZ ≡ double-zeta basis set.

[i] MB ≡ minimal basis set.

[j] Values are taken from Table 1 of Pappas [16].

[k] PCILO ≡ perturbative configuration interaction using localized orbitals method; values are taken from Perahia and Pullman [2].

[l] CNDO/2 ≡ complete neglect of differential overlap method, version 2; values are taken from Leibovici [7].

[m] Minimal *cis* value reported. [n] Maximal *cis* value reported.

[o] Maximal *trans* value reported. [p] Minimal *trans* value reported.

minimum calculated value of E (see Eslava et al. [17] for details). Whether it is better to use values determined experimentally or those calculated by optimization as input parameters in calculating barrier heights remains to be resolved.

We now turn our attention to the effect of including a *d*-type function in the basis set. The results of this inclusion can be seen by comparing corresponding values calculated with the DH and DH + *d* basis sets (see Tables 1 and 2), and can be summarized as follows. First, the molecule is slightly stabilized by the inclusion of this function (from Table 1, $\Delta E_0 \equiv E_{\mathrm{DH}}(90.9°) - E_{\mathrm{DH}+d}(88.2°) =$ 0.088216503 a. u. 55.3 kcal/mol). Second, the calculated heights of the *cis* and *trans* barriers increase by 0.7 and 1.77 kcal/mol, respectively, thereby indicating that interactions with *d* orbitals do contribute to the rotational barriers, as has been suggested by others [4, 11]. Third, the value of $|\theta_0|$ is shifted closer to the experimentally observed values of $|\theta|$. Fourth, the calculated electric dipole moment decreases from 2.66D to 2.21D when $|\theta|$ is taken to be near $|\theta_0|$ [34]. The latter value is closer to the values of 1.97D and 1.985D, as determined by dielectric constant measurements of the compound dissolved in benzene [35] and by Stark effect measurements of the neat compound [19], respectively, than is the former value. Fifth, the calculated value of net charge on each S atom is affected by the inclusion of the *d* function; without the *d* function, the calculated net charge on each S atom is $-0.031\,e$ (i.e. slightly negative) according to the Mulliken definition of charge [36] and $+0.126$ (i.e. positive) according to the Löwdin definition [37] (see Davidson [38] for a discussion of these two population analyses); with the *d* function, these respective values are $-0.141\,e$ and $-0.006\,e$. For the orbitals on the S atom, the largest change in charge as $|\theta|$ is varied from 0° (*cis*) or 180° (*trans*) to around $|\theta_0|$ is found to occur in the d_{xy} orbital [39], when the DH + *d* basis set is used; the maximal population of the d_{xy} occurs when $|\theta|$ is around $|\theta_0|$ i.e. around 90°. This orbital may interact with the p_y orbital [39] on the neighboring S atom [33], thereby contributing to the disulphide bond strength and rotational barrier.

Conclusions

We conclude that all of the basis sets chosen for the present study [28–32] lead to the prediction of reasonable values of *cis* and *trans* barrier heights for the disulphide bridge. The lack of separate, accurate, experimentally determined values of these two barrier heights makes it difficult to decide which basis set and which input geometry is best for use in calculating these barriers in disulphide compounds. We further conclude that the inclusion of a *d*-type function in a basis set for an S atom does lead to a small but readily apparent difference in the calculated value of E, the total energy, and that this difference probably signifies a marginal improvement in the calculated result. For example, for the particular case where the DH basis set [30] is used, this inclusion [32] leads to the calculation of a value of $|\theta_0|$, that is in closer agreement with the experimentally determined value of $|\theta|$.

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[1] Abbreviations used are: *b*, bond length; CNDO, complete neglect of differential overlap; DH, Dunning-Hay; DZ, double-zeta; *e*, elementary charge; E_0, minimum total energy; MB, minimal basis; MO, molecular orbital; PCILO, perturbative configuration interaction using localized orbitals; STO, Slater-type orbitals; ΔE_{cis}, $E(0°)-E_0$, height of *cis* barrier; ΔE_0, E_0 for DH + *d* basis set *relative to* E_0 for DH basis set (i.e., change in E_0 for DH basis set resulting inclusion of *d* function); ΔE_{trans}, $E(180°)-E_0$, height of *trans* barrier; ζ, orbital exponent; θ, torsion angle about S–S; θ_0, torsion angle corresponding to E_0; τ, bond angle.

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