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Molecular Structure and Conformations of *para*-Methylbenzene Sulfonamide and *ortho*-Methylbenzene Sulfonamide: Gas Electron Diffraction and Quantum Chemical Calculations Study

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The molecular structure and conformational properties of *para*-methylbenzene sulfonamide (4-MBSA) and *ortho*-methylbenzene sulfonamide (2-MBSA) have been studied by gas electron diffraction (GED) and quantum chemical methods (B3LYP/6-311+G** and MP2/6-31G**). Quantum chemical calculations predict the existence of two conformers for 4-MBSA with the S−N bond perpendicular to the benzene plane and the NH_2 group either eclipsing or staggering the S−O bonds of the SO_2 group. Both conformers possess C_S symmetry. The eclipsed form is predicted to be favored by $\Delta E = 0.63$ kcal/mol (B3LYP) or 1.00 kcal/mol (MP2). According to the calculations, the S−N bond in 2-MBSA can possess planar direction opposite the methyl group (ϕ(C2C1SN) = 180°) or nonplanar direction (ϕ(C2C1SN) ≈ 60°). In both cases, the NH_2 group can adopt eclipsed or staggered orientation, resulting in a total of four stable conformers. The nonplanar eclipsed conformer (C_1 symmetry) and the planar eclipsed form (C_S symmetry) are predicted to be favored. According to the GED analysis, the saturated vapor over solid 4-MBSA at $T = 151(3)$ °C consists as mixture of the eclipsed (78(19) %) and staggered (22(19) %) forms. The saturated vapor over solid 2-MBSA at $T = 157(3)$ °C consists as a mixture of the nonplanar eclipsed (69(11) %) and planar eclipsed (31(11) %) forms.

Introduction

Sulfonamides are of fundamental chemical interest as many of them possess pharmacological, fungicidal, or herbicidal activities.[1] Some derivatives are potential antitumor agents.[2] It is well known that biological properties correlate strongly with the structure and conformational properties of the respective compound. Recently, we reported the geometric structure and conformation of benzene sulfonamide, $C_6H_5SO_2NH_2$, on the basis of a combined study of gas electron diffraction (GED) and quantum chemical calculations.[3] According to this study, the saturated vapor over solid benzene sulfonamide at a temperature of 150(5) °C consists predominantly as a conformer with the S−N bond perpendicular to the benzene ring and the NH_2 group eclipsing the SO_2 entity. According to calculations, this sterically unfavorable orientation of the NH_2 group is stabilized by *intra*molecular hydrogen bonds between O and H atoms of the sulfonamide group.

In the present study, we report an investigation of the structural and conformational properties of *para*-methylbenzene sulfonamide (4-MBSA) and *ortho*-methylbenzene sulfonamide (2-MBSA) in the gas phase, using GED and quantum chemical calculations. Infrared and NMR spectra of various methyl-substituted benzenesulfonamides have been reported in the literature.[4,5] These data, however, did not provide any information about the structural or conformational properties of these compounds. X-ray studies show that in the crystal 4-MBSA[6,7] and 2-MBSA[8] exist as single conformers with the S−N bond near-perpendicular to the benzene ring and with the NH_2 group in staggered orientation. This orientation is stabilized by short O···H distances between neighboring molecules forming strong *inter*molecular hydrogen bonds.

Quantum Chemical Calculations. Structure optimizations and frequency calculations for both derivatives were performed with the DFT method B3LYP/6-311+G** and with the ab initio approximation MP2/6-31G** using the *Gaussian 03* program system.[9] For 4-MBSA, two stable conformers exist. Both conformers possess C_S symmetry with the S−N bond and one C−H bond of the methyl group perpendicular to the benzene ring (ϕ(C2−C1−S−N) = 90° and ϕ(C3−C4−C7−H1) = 90°; see Figure 1a for atom numbering). The two forms differ by the orientation of the NH_2 group, either eclipsing the SO_2 moiety or staggering the S−C bond. The sterically unfavorable form with both N−H bonds eclipsing the S═O bonds is predicted to be favored by $\Delta E = E(\text{stag}) - E(\text{ecl}) = 0.63$ kcal/mol (B3LYP) and 1.00 (MP2), respectively. The calculated Gibbs free energy differences $\Delta G°$ at the temperature of the GED experiment (150 °C) are 1.65 kcal/mol (B3LYP) and 4.19 kcal/mol (MP2). The large differences between ΔE and $\Delta G°$ values are predominantly due to low frequency torsional vibrations around the $C-CH_3$ and $C-SO_2NH_2$ bonds for which MP2 and B3LYP methods predict rather different values. Particularly, a much lower $C-SO_2NH_2$ torsional frequency in the eclipsed form compared to that in the staggered conformer is predicted, resulting in higher entropy. An unreasonably low torsional frequency of 3 cm^{-1} in the eclipsed form is predicted by the MP2 method. Thus, calculated $\Delta G°$ values may not be very reliable. The

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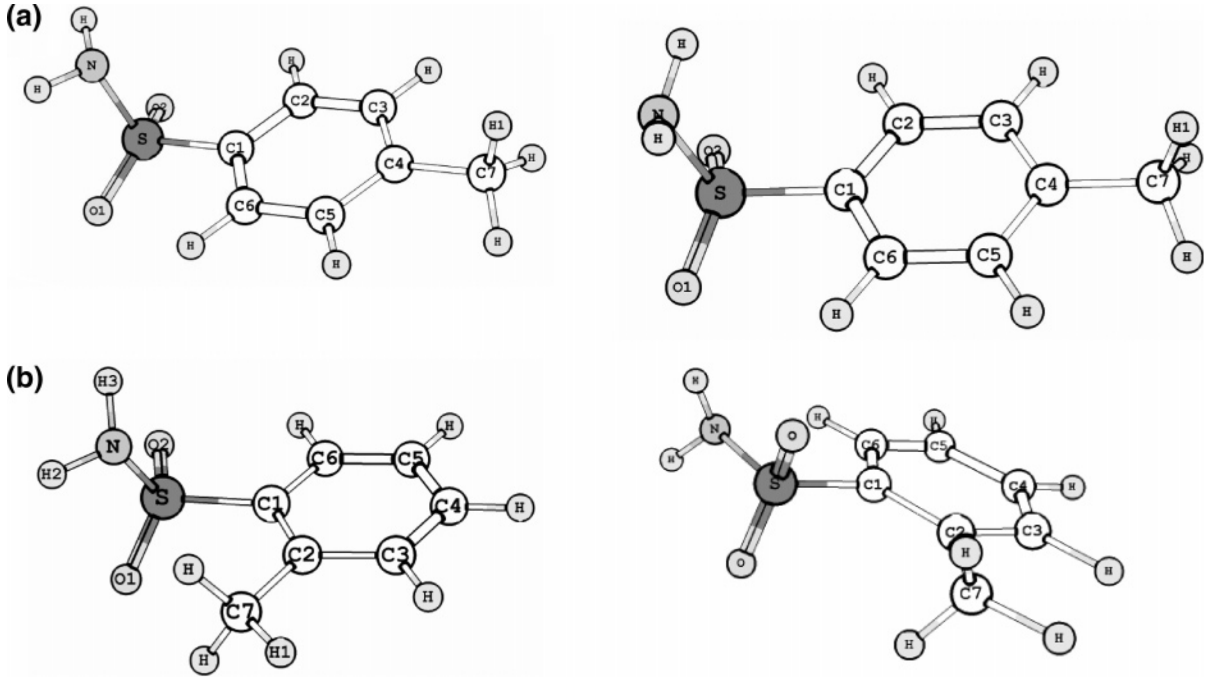

Figure 1. Molecular models with atom numbering. (1a) *para*-Methylbenzene sulfonamide. (1b) *ortho*-Methylbenzene sulfonamide.

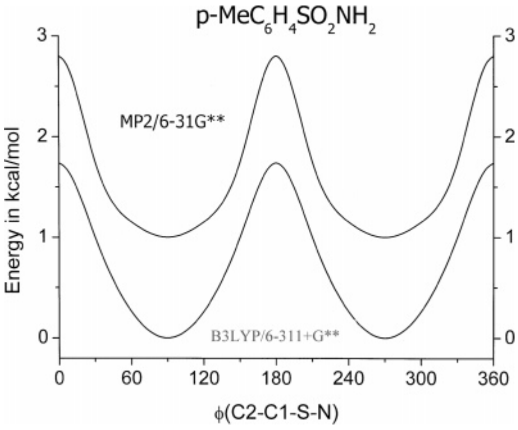

Figure 2. Calculated potential functions for internal rotation around the C1−S bond in *para*-methylbenzene sulfonamide. The MP2 curve is shifted by 1 kcal/mol.

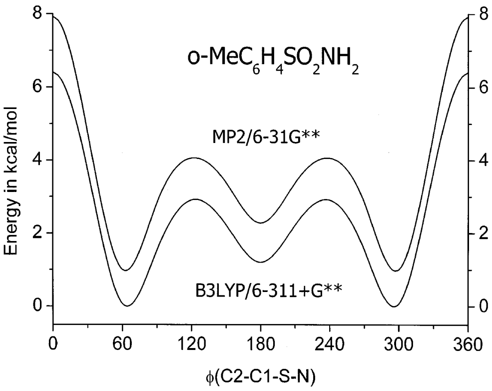

Figure 3. Calculated potential functions for internal rotation around the C1−S bond in *ortho*-methylbenzene sulfonamide. The MP2 curve is shifted by 1 kcal/mol.

TABLE 1: Calculated Relative Energies and Gibbs Free Energies (kcal/mol) of the Four Stable Conformers of *ortho*-Methylbenzene Sulfonamide

	nonplanar/ eclipsed	planar/ eclipsed	nonplanar/ staggered	planar/ staggered
B3LYP/6-311+G**				
ΔE	0.00	1.20	1.65	3.25
$\Delta G^{\circ\, a}$	0.00	0.60	1.37	3.00
MP2/6-31G**				
ΔE	0.00	1.30	2.31	3.67
$\Delta G^{\circ\, a}$	0.00	1.68	2.92	3.95

[a] At 157 °C (430 K). The values account for the different multiplicities of planar ($m = 1$) and nonplanar ($m = 2$) conformers.

structure with parallel orientation of the S−N bond (ϕ(C2−C1−S−N) = 0° or 180°) corresponds to a transition state. The potential function for internal rotation around the C1−S bond (for eclipsed orientation of the NH_2 group) is shown in Figure 2. This curve was derived by optimizing the geometric structures at different fixed dihedral angles ϕ(C2−C1−S−N). The barrier at the planar orientation is 1.75 kcal/mol. The potential function for internal rotation around the S−N bond from eclipsed to staggered orientation has been derived with the B3LYP method (not shown). The barrier for rotating from eclipsed to staggered orientation is 4.37 kcal/mol. The methyl group performs free internal rotation around the C4−C7 bond with a calculated (B3LYP) barrier of only 0.03 kcal/mol.

Similar calculations for 2-MBSA result in the presence of four stable conformers. Both computational methods, B3LYP and MP2, predict similar potential functions for internal rotation around the C−S bond (Figure 3) with minima at nonplanar orientation (ϕ(C2−C1−S−N) near 60° and 300°) and planar orientation with the S−N bond pointing away from the methyl group (ϕ(C2−C1−S−N) = 180°). In both cases, the NH_2 group can adopt either an eclipsed or staggered orientation. The barrier between nonplanar and planar conformer is predicted to be 2.9 (B3LYP) and 3.0 (MP2) kcal/mol. The relative energies and Gibbs free energies of the four stable conformers are listed in Table 1. ΔG° values account for the different multiplicities of nonplanar ($m = 2$) and planar ($m = 1$) conformers. Again, rather large differences between ΔE and ΔG° values in some cases are due to differences in low frequency torsional vibrations. The orientation of the methyl group in this ortho-substituted compound differs from that in the para-substituted sulfonamide.

TABLE 2: Conditions of the Simultaneous GED/MS Experiments

	para-methylbenzene sulfonamide		*ortho*-methylbenzene sulfonamide	
nozzle-to-plate distance, mm	338	598	338	598
electron beam current, μA	1.3	2.1	1.9	2.5
accelerating voltage, kV	93	91	93	93
temperature of effusion cell, °C	150(3)	151(3)	157(3)	157(3)
ionization voltage, V	50	50	50	50
exposure time, s	90	70	60	150
residual gas pressure, Torr	2.8×10^{-6}	4.5×10^{-6}	1.8×10^{-6}	4.4×10^{-6}
scattering angles, Å^{-1}	2.8−31.2	1.3−17.5	2.7−31.3	1.3−17.5

TABLE 3: Mass Spectra of the Saturated Vapor of *para*-Methylbenzene Sulfonamide, $4\text{-}CH_3-C_6H_4-SO_2NH_2$, and *ortho*-Methylbenzene Sulfonamide, $2\text{-}CH_3-C_6H_4-SO_2NH_2$, Recorded at $U_{ioniz} = 50$ V Simultaneously with the Diffraction Pattern

		abundance (relative to $[C_7H_7]^+$, %)	
ion	m/e au	*para*-methylbenzene sulfonamide	*ortho*-methylbenzene sulfonamide
$[CH_3C_6H_4SO_2NH_2]^+$	171	29	18
$[C_6H_4SO_2NH_2]^+$	156	26	4
$[C_6H_4SO_2]^+$	140	2	11
$[C_6H_4SO]^+$	124	3	3
$[CH_3C_4H_2SO]^+$	113	3	4
$[C_6H_4S]^+$	108	17	18
$[C_6H_3S]^+$	107	27	60
$[^{13}C_1{}^{12}C_6H_7]^+$, $[C-SO_2NH_2]^+$	92	11	91
$[C_7H_7]^+$	91	100	100
$[CH_3C_6H_2]^+$	89	12	35
$[SO_2NH]^+$	79	5	15
$[SO_2]^+$	64	16	24
$[C_4H_3]^+$	51	6	11

Whereas one C−H bond in 4-MBSA is perpendicular to the benzene plane (ϕ(C3−C4−C7−H) = 90°), it is parallel in 2-MBSA (ϕ(C1−C2−C7−H1) = 180°). Because of steric interactions with the SO_2NH_2 group in the ortho position, the calculated (B3LYP) barrier to internal rotation of the methyl group is much higher (1.4 kcal/mol in 2-MBSA compared to 0.03 kcal/mol in 4-MBSA).

Experimental Section

Electron diffraction patterns were recorded with the apparatus described in ref 10. The effusion cell of molybdenum with a cylindrical nozzle of 0.6×1.0 mm^2 size (diameter × length) was used for evaporation of the samples at 157(3) °C and 151(3) °C for 2-MBSA and 4-MBSA, respectively. The temperature of the effusion cell was measured by a thermocouple W/Re-5/20. The electron wavelength was obtained from diffraction patterns of polycrystalline ZnO. Commercial samples of methylbenzene sulfonamides were purified by recrystallization twice from water−2-propanol mixture (20% alcohol), until the melting point of *ortho*-methylbenzene sulfonamide was 155.0(0.2) °C (literature mp 156 °C[11]), and until the melting point of *para*-methylbenzene sulfonamide was 138.0−139.0(0.2) °C (literature mp 139 °C[11]).

For both compounds, the mass spectrum of the vapor was recorded simultaneously with the registration of the diffraction pattern. In both cases, the heaviest ion was the monomeric parent ion. The conditions of combined gas electron diffraction and mass spectrometric experiments (GED/MS) are listed in Table 2. The mass spectra shown in Table 3 demonstrate that the vapor of both compounds consists of only one species with the stoichiometry $CH_3–C_6H_4–SO_2NH_2$ and the absence of detectable amounts of volatile impurities in the samples.

Optical densities of the plates were measured by the computer-controlled MD-100 microdensitometer.[12] For the microphotometric measurements, six plates for each, long and short camera distance, were taken. The rectangular area of about 130×15 mm^2 was scanned along the diagonal of the plates. The data array for the diagonal consisted of 33 lines, 1299 points each. The step width along a scan line was 0.1 mm, and the distance between the lines was about 0.28 mm. The scanning of the films with ZnO diffraction patterns for calibration of electron wavelength was done with a step width of 0.0125 mm. The background functions G(s) for the intensities I(s) of the long and short camera distances were approximated by smooth lines. The analysis of the first- and second-order derivatives of the G(s) functions was used to check the absence of the oscillations of G(s), which could be close to the oscillations of the sM(s) function. No elimination of the frequency oscillations was done. The molecular intensities sM(s) were obtained in the ranges 3.2−31.2 and 1.4−17.2 Å^{-1} (4-MBSA) and 2.7−31.3 and 1.3−16.6 Å^{-1} (2-MBSA) for the short and long camera distances, respectively. Experimental and calculated intensities with residuals for 4-MBSA are presented in Figure 4; those for 2-MBSA are shown in Figure S1 in Supporting Information.

Structural Analysis. A conventional least-squares analysis of sM(s) was carried out using a modified version of the KCED program.[13] Scattering functions of ref 14 were used to calculate the theoretical molecular intensities. The starting values for bond distances and angles were taken from the B3LYP/6-311+G** calculations. Vibrational corrections, $\Delta r = r_{h1} - r_a$, and the starting values for vibrational amplitudes were derived from calculated force fields (B3LYP/6-311+G**) using the approach of Sipachev, which is incorporated in the program SHRINK.[15]

4-MBSA. The experimental radial distribution function, which is derived by Fourier transformation of the experimental

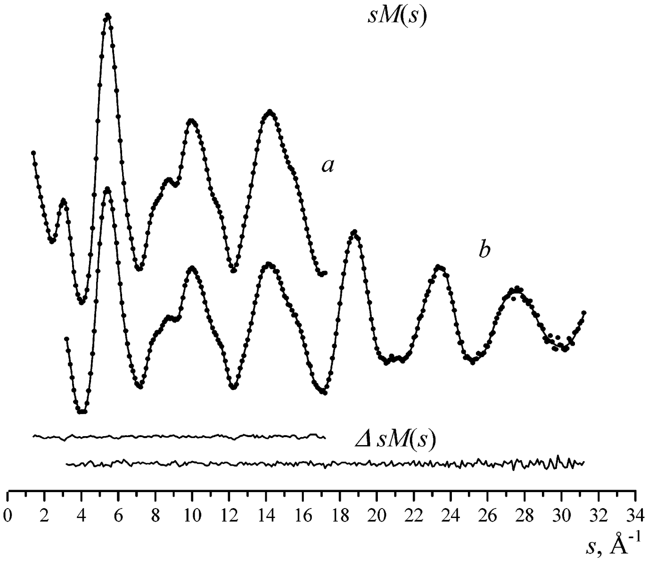

Figure 4. Experimental (●) and calculated (—) molecular intensities sM(s) and residuals for *para*-methylbenzene sulfonamide for the long (a) and short (b) nozzle-to-plate distances.

TABLE 4: Experimental and Calculated Structural Parameters of Eclipsed and Staggered Conformers of 4-MBSA, 4-$CH_3-C_6H_4SO_2NH_2$ (Distances in Å, Angles in Deg)

	eclipsed		staggered	
parameter	GED[a] r_{h1} structure	B3LYP/6-311+G** r_e structure	GED[a] r_{h1} structure	B3LYP/6-311+G** r_e structure
C3−H[b]	1.090(11) p_1	1.084	1.090(11) (p_1)	1.084
C7−H[b]	1.099(11) (p_1)	1.093	1.099(11) (p_1)	1.093
N−H[b]	1.024(39) (p_1)	1.015	1.023(39) (p_1)	1.014
C1−C2	1.398(4) p_2	1.392	1.397(4) (p_2)	1.393
C2−C3	1.397(4) (p_2)	1.391	1.399(4) (p_2)	1.392
C3−C4	1.406(4) (p_2)	1.400	1.406(4) (p_2)	1.400
C1−S	1.770(7) p_3	1.794	1.778(7) (p_3)	1.802
S−N	1.682(5) p_4	1.696	1.669(5) (p_4)	1.684
S−O[b]	1.432(4) p_5	1.462	1.428(4) (p_5)	1.457
C4−C7	1.505(9) p_6	1.508	1.505(9) (p_6)	1.508
∠C2−C1−C6	121.2(2) p_7	121.1	121.4(2) (p_7)	120.9
∠C1−C2−C3	119.1(2) (p_7)	119.0	119.2(2) (p_7)	119.1
∠C2−C3−C4	120.8(7) (p_7)	121.2	120.1(7) (p_7)	121.2
∠C3−C4−C5	119.0(9) (p_7)	118.4	120.0(9) (p_7)	118.4
∠C1−S−N	103.3(17) p_8	103.7	106.9(17) (p_8)	107.4
∠C1−S−O	107.9(6) p_9	107.7	107.6(6) (p_9)	107.5
∠N−S−O	106.0(17) p_{10}	106.9	104.4(17) (p_{10})	105.3
∠S−N−H	108.2(34) p_{11}	110.1	111.0(34) (p_{11})	112.9
∠H−N−H	113.5(34)	111.6	115.1(41)	112.8
∠C4−C7−H1, single	108.7(97) p_{12}	110.7	108.7(97) (p_{12})	110.7
∠C4−C7−H, double	109.4(97) (p_{12})	111.4	109.4(97) (p_{12})	111.4
ϕ(C3−C4−C7−H1)[c]	90.0	90.0	90.0	90.0
ϕ(C2−C1−S−N)[c]	90.0	90.0	90.0	90.0
ϕ(C1−S−N−H)[c]	118.3	118.3	64.7	64.7
mol %	78(19)	88	22(19)	12
R_f, %	3.33			

[a] The total error limit in interatomic distances was estimated by formula $\sigma = [(2.5\sigma_{LS})^2 + (0.002r)^2]^{1/2}$. Total error in the angles and in mole fraction was taken to be equal $3\sigma_{LS}$ (in the units of last significant digit). [b] Average value in eclipsed and staggered conformer. [c] Not refined.

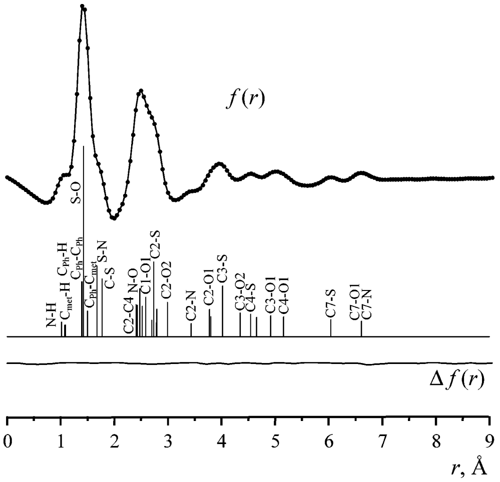

Figure 5. Experimental (●) and theoretical (−) radial distribution function for *para*-methylbenzene sulfonamide and residual curve for optimal mixture of eclipsed and staggered conformers.

intensities, is shown in Figure 5. The theoretical sM(s) function was calculated assuming that the vapor consists of a mixture of eclipsed and staggered conformers. Considering the barriers to internal rotation around the C1−S and S−N bonds (see above), a rigid model is adequate in the analysis of the GED intensities. The free rotation of the methyl group has no detectable effect on the molecular intensities. On the basis of quantum chemical calculation results, the following assumptions were made to describe the molecular geometry of each conformer in the least-squares refinements: (1) C_S overall symmetry is assumed for eclipsed and staggered conformers and local C_S symmetry for the CH_3 group, (2) all atoms of the $C7-C_6H_4-S$ fragment lie in the same plane, (3) all $C_{Ph}-H$ bonds in the ring possess equal length and bisect the adjacent −C−C−C angle, (4) all $C_{meth}-H$ bond lengths are equal and the difference between the C−C−H1 and C−C−H bond angles is set to the calculated value, (5) differences between $C_{Ph}-H$, $C_{meth}-H$, and N−H bond lengths, between C−C bond lengths, and between C−C−C bond angles in the benzene ring are constrained to calculated values, (6) the ϕ(C−S−N−H) dihedral angles in the eclipsed and staggered conformer are set to calculated values, and (7) vibrational amplitudes are collected in 11 groups and differences within each group are constrained to calculated values.

With these assumptions, 12 independent structural parameters for each conformer of 4-MBSA (p_1 to p_{12} in Table 4) were refined in the least-squares analysis: six bond distances (C1−C2, $C_{Ph}-H$, C4−C7, C1−S, S−N, S═O) and six bond angles (−C2−C1−C6, −C1−S−N, −C1−S═O, −S−N−H, −N−S═O, −C4−C7−H1). Preliminary least-squares analyses showed that the *R*-factor is sensitive toward the torsion angle of the SO_2NH_2 around the C1−S bond (ϕ(C2−C1−S−N). Independent of the starting value between 50° and 90°, this angle converged toward 90°. Therefore, this parameter was kept at 90° in all further refinements (C_S overall symmetry). In the next step, least-square refinements were carried out assuming the presence of a single conformer, eclipsed or staggered. The agreement factors R_f were rather similar for both conformers: 3.37% for the eclipsed form and 3.50% for the staggered one. Figure 6 shows R_f values derived from least-squares refinements with fixed percentages of the eclipsed form. The uncertainty at a significance level of 0.05 derived with Hamilton's method[16] demonstrates that GED intensities possess a low sensitivity toward this conformational composition.

In the final stage, least-squares analyses for mixtures of both conformers were carried out. In addition to the geometric

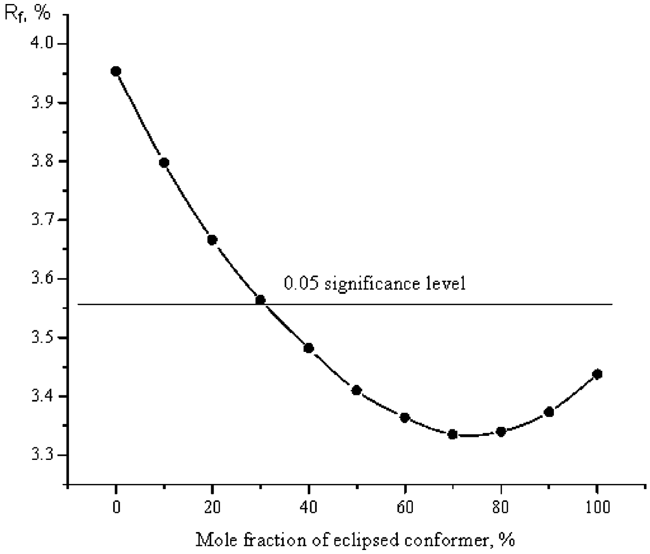

Figure 6. Disagreement factor R_f for different contributions of eclipsed conformer of *para*-methylbenzene sulfonamide.

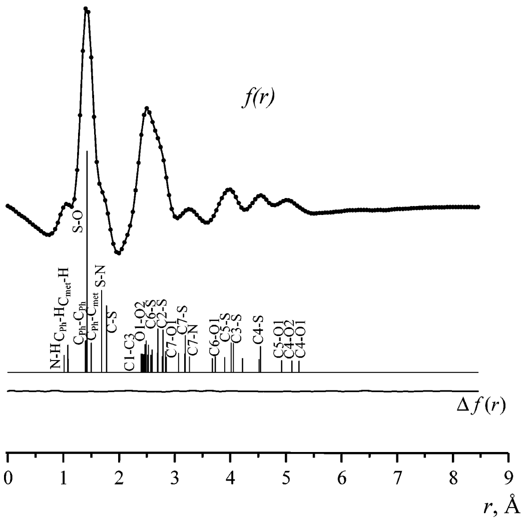

Figure 7. Experimental (●) and theoretical (—) radial distribution function for *ortho*-methylbenzene sulfonamide and residual curve for optimal mixture of nonplanar eclipsed and planar eclipsed conformers.

parameters and vibrational amplitudes of the prevailing eclipsed form, the vapor composition was refined. All parameters of the staggered conformer were tied to those of the eclipsed form using the calculated differences. Seven correlation coefficients had an absolute value larger than 0.7: $p_1/p_5 = -0.76$, $p_3/p_8 = -0.94$, $p_1/p_{10} = -0.93$, $p_5/p_{10} = 0.73$, $p_1/p_{12} = -0.91$, $p_5/p_{12} = 0.78$, $p_{10}/p_{12} = 0.87$. The best agreement between experimental and calculated sM(s) functions was achieved for a mixture of 78(19) mol % eclipsed and 22(19) mol % staggered conformers. Experimental and calculated geometric parameters of both conformers are listed in Table 4, and interatomic distances, vibrational amplitudes, and vibrational corrections for the prevailing eclipsed conformer are listed in Table 5, and those for the minor staggered form are given as Supporting Information (Table S1).

2-MBSA. The experimental radial distribution curve is shown in Figure 7. Quantum chemical calculations predict for this compound the existence of four stable conformers. Only the two conformers with eclipsed orientation of the NH_2 group, nonplanar and planar, were considered in the GED analysis, since those two are preferred according to both computational methods (Table 1) and GED intensities are not sensitive toward eclipsed or staggered orientation of the NH_2 group. Similar assumptions as in the case of 4-MBSA were adopted to describe the molecular geometries of each conformer in the least-squares refinement: (1) C_S overall symmetry for planar eclipsed conformer and local C_{3v} symmetry for the methyl group in both conformers, (2) all atoms of the $C7-C_6H_4-S$ fragment of both conformers lie in the same plane, (3) all $C_{Ph}-H$ bonds in the ring possess equal length and bisect the adjacent −C−C−C angles, (4) all $C_{meth}-H$ bond lengths are equal and one C−H bond lies in the benzene plane ($\phi(C1-C2-C7-H1) = 180°$), (5) differences between $C_{Ph}-H$, $C_{meth}-H$, and N−H bond lengths, between C−C bond lengths, between C−C−C bond angles in the benzene ring, between S=O bond lengths, C1−S=O, N−S=O, and S−N−H bond angles in the nonplanar conformer are constrained to calculated values, (6) the angles −H−N−H and $\phi(C-S-N-H2)$ are set to calculated values, and (7) vibrational amplitudes are collected in seven groups and differences between amplitudes in each group are constrained to calculated values.

TABLE 5: Experimental Interatomic Distances, Experimental and Calculated Vibrational Amplitudes, and Vibrational Corrections (without Nonbonded Distances Involving Hydrogen Atoms) for 4-MBSA, $4-CH_3-C_6H_4-SO_2NH_2$ (Eclipsed Conformer)

parameter	r_a	l_{expt}	l_{calcd}	$\Delta r = r_{h1} - r_a$	no. group
N−H[b]	1.018(16)	0.074(4)[a]	0.080	0.006	1
C3−H[b]	1.085(4)	0.069(4)	0.075	0.005	1
C7−H[b]	1.086(4)	0.074(4)	0.081	0.006	1
C2−C3	1.395(1)	0.048(0.5)	0.047	0.002	1
C1−C2	1.396(1)	0.048(0.5)	0.047	0.001	2
C3−C4	1.404(1)	0.048(0.5)	0.048	0.002	2
S−O[b]	1.431(1)	0.038(0.5)	0.037	0.001	2
C4−C7	1.503(4)	0.051(0.5)	0.051	0.002	2
S−N	1.680(2)	0.058(2)	0.053	0.002	3
C1−S	1.769(2)	0.059(2)	0.054	0.002	3
C1−C3	2.405(2)	0.047(1)	0.057	0.005	4
C3−C5	2.415(5)	0.047(1)	0.057	0.006	4
C2−C6	2.430(2)	0.046(1)	0.056	0.006	4
C2−C4	2.432(3)	0.046(1)	0.056	0.005	4
N−O1	2.481(9)	0.105(1)	0.115	0.010	4
C3−C7	2.521(2)	0.062(1)	0.072	0.006	4
O−O	2.525(8)	0.053(1)	0.063	0.004	4
C1−O1	2.592(3)	0.072(1)	0.082	0.005	4
C1−N	2.703(10)	0.088(2)	0.094	0.005	5
C2−S	2.736(2)	0.067(2)	0.072	0.006	5
C1−C4	2.788(4)	0.058(2)	0.064	0.009	5
C2−C5	2.796(3)	0.059(2)	0.064	0.006	5
C2−O2	2.994(4)	0.190(8)	0.204	−0.053	6
C2−N	3.438(11)	0.326(8)	0.359	0.062	6
C2−O1	3.777(3)	0.140(2)	0.131	0.071	7
C2−C7	3.802(2)	0.082(2)	0.072	0.014	7
C3−S	4.025(1)	0.081(2)	0.071	0.014	7
C1−C7	4.284(3)	0.072(3)	0.072	0.018	8
C3−O2	4.352(4)	0.177(3)	0.177	−0.029	8
C4−S	4.548(4)	0.072(3)	0.072	0.020	8
C3−N	4.659(13)	0.300(3)	0.300	0.045	8
C3−O1	4.917(4)	0.147(7)	0.122	0.064	9
C4−O1	5.164(5)	0.154(7)	0.129	0.025	9
C4−N	5.188(13)	0.200(7)	0.175	0.030	9
C7−S	6.040(3)	0.098(6)	0.080	0.032	10
C7−O1	6.615(4)	0.131(6)	0.146	0.038	11
C7−N	6.616(15)	0.193(6)	0.207	0.047	11

[a] σ_{LS}. [b] Average value in eclipsed conformer.

With these assumptions, 12 independent structural parameters were refined for the nonplanar conformer in the least-squares refinements: six bond distances (C1−C2, $C_{Ph}-H$, C2−C7, C1−S, S−N, S=O) and six bond angles (−C2−C1−C6, −C1−S−N, −C1−S=O2, −N−S=O2, −S−N−H, −C2−C7−H). In the first stage of structural analysis, refinements were performed

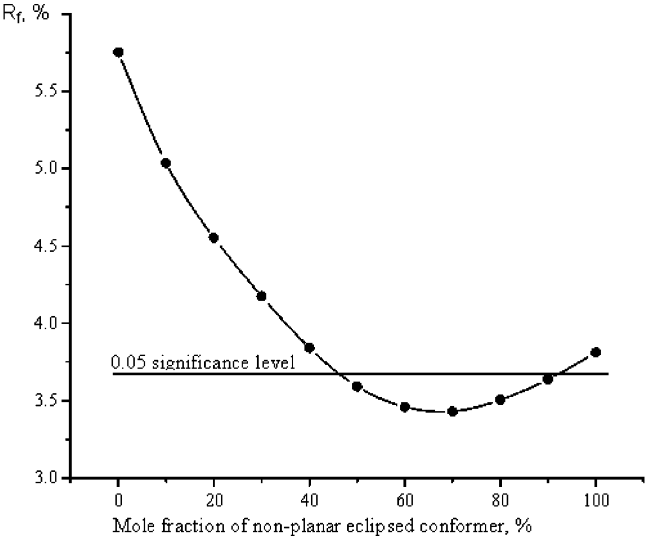

Figure 8. Disagreement factor R_f for different contributions of nonplanar eclipsed conformer of *ortho*-methylbenzene sulfonamide.

assuming the presence of a single conformer, nonplanar eclipsed or planar eclipsed. In contrast to 4-MBSA, the difference between R_f values for both conformers was significant: 3.81% for nonplanar eclipsed conformer and 5.75% for planar eclipsed conformer. The plot of R_f values derived for different fixed conformational compositions and Hamilton's uncertainty at 0.05 significance level (Figure 8) demonstrate that the nonplanar form is prevailing and GED intensities possess a higher sensitivity toward this conformational composition.

Finally, all 12 structural parameters of the nonplanar eclipsed conformer (p_1 to p_{12} in Table 6) and the vapor composition were refined simultaneously together with the seven groups of vibrational amplitudes. Geometric parameters of the planar form were tied to those of the nonplanar conformer using calculated differences. Only two correlation coefficients, $p_1/p_9 = -0.81$, $p_7/p_{10} = -0.84$, had absolute values larger than 0.7. The geometric parameters for both conformers and the conformational composition are listed in Table 6, and interatomic distances, vibrational amplitudes, and vibrational corrections of the prevailing nonplanar form are listed in Table 7. The values for the minor planar conformer are given as Supporting Information (Table S2).

Discussion

Quantum chemical calculations predict the presence of two conformers of gaseous 4-MBSA, eclipsed (N−H bonds eclipse S═O bonds) and staggered (NH_2 group staggers the S−C bond), each of which possesses C_S symmetry with the eclipsed conformer lower in energy than the staggered conformer by 0.63

TABLE 6: Experimental and Calculated Structural Parameters of 2-MBSA, $2\text{-}CH_3\text{-}C_6H_4SO_2NH_2$ (Distances in Å, Angles in Deg)

	nonplanar eclipsed		planar eclipsed	
parameter	GED[a] r_{h1} structure	B3LYP/6-311+G** r_e structure	GED r_{h1} structure	B3LYP/6-311+G** r_e structure
C3−H[b]	1.085(3) p_1	1.084	1.084(3) (p_1)	1.083
C7−H[b]	1.093(4) (p_1)	1.092	1.093(4) (p_1)	1.092
N−H[b]	1.017(4) (p_1)	1.016	1.016(4)(p_1)	1.015
C1−C2	1.417(3) p_2	1.408	1.419(3) (p_2)	1.409
C2−C3	1.409(3) (p_2)	1.399	1.408(3) (p_2)	1.398
C1−C6	1.404(3) (p_2)	1.395	1.403(3) (p_2)	1.393
C3−C4	1.403(3) (p_2)	1.393	1.403(3) (p_2)	1.393
C4−C5	1.401(3) (p_2)	1.391	1.400(3) (p_2)	1.390
C5−C6	1.401(3) (p_2)	1.392	1.403(3) (p_2)	1.393
C2−C7	1.505(7) p_3	1.507	1.506(7) (p_3)	1.509
C1−S	1.779(4) p_4	1.804	1.782(4) (p_4)	1.807
S−N	1.687(4) p_5	1.699	1.679(4) (p_5)	1.690
S−O[b]	1.429(3) p_6	1.462	1.430(3) (p_6)	1.463
∠C2−C1−C6	122.2(2) p_7	122.2	122.1 (2) (p_7)	122.1
∠C1−C2−C3	116.5(2) (p_7)	116.5	116.6(2) (p_7)	116.6
∠C2−C3−C4	121.8(6) (p_7)	122.1	122.4(6) (p_7)	122.0
∠C3−C4−C5	120.5(9) (p_7)	120.2	119.4(9) (p_7)	120.1
∠C4−C5−C6	119.2(6) (p_7)	119.4	119.6(6) (p_7)	119.5
∠C1−C6−C5	119.8(2) (p_7)	119.8	119.7(2) (p_7)	119.7
∠C1−C2−C7	123.7(3) (p_7)	123.8	123.5(3) (p_7)	123.4
∠C2−C1−S	121.8(2) (p_7)	121.8	118.0(2) (p_7)	118.0
∠C1−S−N	102.1(17) p_8	102.8	103.1(17) (p_8)	103.8
∠C1−S−O1	110.4(8) (p_9)	109.6	107.4(8) (p_9)	108.3
∠C1−S−O2	107.8(8) p_9	107.3	107.4(8) (p_9)	108.3
∠N−S−O2	108.6(21) p_{10}	109.2	106.6(21) (p_{10})	107.3
∠N−S−O1	104.7(21) (p_{10})	105.4	106.6(21) (p_{10})	107.3
∠H2−N−S	108.3(25) p_{11}	108.6	110.4(25) (p_{11})	109.9
∠H3−N−S	110.1(25) (p_{11})	110.4	110.4(25) (p_{11})	109.9
∠H−N−H	110.8(25)	110.8	111.7(25)	112.0
∠C2−C7−H	111.6(38) p_{12}	110.8	112.1(38) (p_{12})	110.9
ϕ(C1−C2−C7−H1)[c]	180.0	180.0	180.0	180.0
ϕ(C2−C1−S−N)[c]	64.3	64.3	180.0	180.0
ϕ(H1−N−S−C1)[c]	141.6	141.6	118.0	118.0
mol %	68(11)	69	32(11)	31
R_f, %	3.43			

[a] The total error limit in interatomic distances was estimated by formula $\sigma = [(2.5\sigma_{LS})^2 + (0.002r)^2]^{1/2}$. Total error in the angles and in mole fraction was taken to be equal $3\sigma_{LS}$ (in the units of last significant digit). [b] Average value in nonplanar and planar eclipsed conformer. [c] Not refined.

TABLE 7: Experimental Interatomic Distances, Experimental and Calculated Vibrational Amplitudes, and Vibrational Corrections (without Nonbonded Distances Involving Hydrogen Atoms) for 2-MBSA, $2\text{-}CH_3-C_6H_4-SO_2NH_2$ (Nonplanar Eclipsed Conformer)

parameter	r_a	l_{expt}	l_{calcd}	$\Delta r = r_{h1} - r_a$	No. group
N−H[b]	1.012(1)[a]	0.065(1)[a]	0.071	0.005	1
C3−H[b]	1.080(1)	0.070(1)	0.075	0.005	1
C7−H[b]	1.087(1)	0.071(1)	0.077	0.005	1
C4−C6	1.400(0.5)	0.046(0.3)	0.046	0.001	2
C5−C6	1.400(0.5)	0.046(0.3)	0.046	0.001	2
C3−C4	1.402(0.5)	0.046(0.3)	0.046	0.001	2
C1−C6	1.403(0.5)	0.046(0.3)	0.046	0.002	2
C2−C3	1.407(0.5)	0.046(0.3)	0.046	0.002	2
C1−C2	1.415(0.5)	0.047(0.3)	0.047	0.002	2
C2−C7	1.503(2)	0.051(0.3)	0.051	0.002	2
S−O[b]	1.429(0.4)	0.037(0.3)	0.037	0.001	2
S−N	1.686(1)	0.054(0.3)	0.053	0.002	2
C1−S	1.777(1)	0.055(0.3)	0.055	0.002	2
C1−C3	2.398(1)	0.056(1)	0.058	0.006	3
C4−C6	2.412(2)	0.055(1)	0.056	0.005	3
C1−C5	2.422(1)	0.055(1)	0.057	0.006	3
C3−C5	2.429(3)	0.055(1)	0.056	0.005	3
C2−C4	2.451(2)	0.055(1)	0.056	0.006	3
C2−C6	2.464(1)	0.055(1)	0.057	0.006	3
C3−C7	2.515(2)	0.066(1)	0.067	0.007	3
N−O1	2.469(10)	0.078(1)	0.080	0.005	3
O1−O2	2.491(12)	0.063(1)	0.064	0.004	3
C1−C7	2.570(2)	0.066(1)	0.068	0.007	3
N−O2	2.529(10)	0.085(1)	0.086	0.006	3
C1−O2	2.595(5)	0.075(1)	0.076	0.004	3
C1−O1	2.636(5)	0.084(1)	0.086	0.005	3
C6−S	2.699(1)	0.067(1)	0.068	0.007	3
C1−N	2.690(10)	0.097(1)	0.098	0.006	3
C1−C4	2.775(3)	0.063(1)	0.064	0.008	3
C3−C6	2.789(2)	0.063(1)	0.064	0.007	3
C2−S	2.792(1)	0.068(1)	0.069	0.007	3
C2−C5	2.849(2)	0.062(1)	0.064	0.008	3
C6−O2	2.835(7)	0.111(1)	0.112	−0.003	3
C7−O1	3.069(8)	0.211(3)	0.211	0.005	4
C7−S	3.194(1)	0.102(3)	0.103	0.007	4
C2−O1	3.182(4)	0.134(3)	0.134	0.008	4
C7−N	3.265(10)	0.235(3)	0.235	0.014	4
C2−N	3.266(13)	0.151(3)	0.151	0.011	4
C6−N	3.676(9)	0.153(2)	0.153	0.022	5
C6−O1	3.730(8)	0.129(2)	0.124	0.021	5
C4−C7	3.811(2)	0.074(2)	0.069	0.014	5
C6−C7	3.854(3)	0.074(2)	0.069	0.014	5
C2−O2	3.902(4)	0.082(2)	0.077	0.017	5
C5−S	4.013(1)	0.075(2)	0.070	0.014	5
C3−S	4.058(1)	0.075(2)	0.071	0.015	5
C5−O2	4.221(7)	0.118(3)	0.118	0.007	6
C5−C7	4.344(4)	0.072(3)	0.072	0.017	6
C3−O1	4.516(5)	0.141(3)	0.141	0.019	6
C4−S	4.541(3)	0.072(3)	0.073	0.018	6
C3−N	4.526(14)	0.164(3)	0.165	0.022	6
C7−O2	4.553(2)	0.101(3)	0.102	0.024	6
C4−N	4.838(12)	0.169(8)	0.173	0.030	7
C5−O1	4.924(8)	0.135(8)	0.139	0.029	7
C3−O2	4.976(5)	0.082(8)	0.087	0.022	7
C4−O2	5.110(7)	0.101(8)	0.106	0.018	7
C4−N	5.178(13)	0.167(8)	0.171	0.029	7
C4−O1	5.234(7)	0.136(8)	0.141	0.028	7

[a] σ_{LS}. [b] Average value in eclipsed nonplanar conformer.

kcal/mol (B3LYP/6-311+G**) or by 1.00 kcal/mol (MP2/6-31G**). According to relative free energies ($\Delta G^\circ = 1.65$ and 4.19 kcal/mol, respectively), the eclipsed conformer should be strongly prevailing (88% and ~100% from B3LYP and MP2, respectively) at the condition of the GED experiment. These values are in reasonable agreement with the experimental result of 78(19) %, corresponding to $\Delta G^\circ = 1.1(8)$ kcal/mol. It has been pointed out above that calculated ΔG° values, especially that derived with the MP2 method, have to be considered with caution because of unreasonably small values predicted for torsional frequencies. The conformational composition of 4-MBSA is very similar to that of the unsubstituted benzenesulfonamide, for which also the preference of the eclipsed conformer in the gas phase was observed.[3] In both compounds, unsubstituted and *p*-methyl-substituted benzenesulphonamide, the S−N bond is oriented perpendicular to the benzene ring. Calculations predict the energy for the planar orientation (Figure 2) to be higher by only about 1.7 to 1.8 kcal/mol, and the slight preference for perpendicular orientation is considered to be a delicate balance between steric repulsions and electronic interactions. Calculated structural parameters for 4-MBSA are very close to experimental parameters (Table 4) excluding bond lengths involving sulfur, especially the S═O bond. It is well known that calculations with relatively small basis sets overestimate S−X bond lengths if X is an electronegative element. The addition of diffuse functions to the basis set makes the agreement between theory and experiment closer but does not solve the problem completely. Very reasonable agreement is obtained between experimental and calculated values of vibrational amplitudes (Tables 5 and S1).

For 2-MBSA, the calculations predict four stable conformers: nonplanar eclipsed and planar eclipsed, nonplanar staggered and planar staggered (Table 1). Since both staggered conformers are higher in energy and GED intensities are not sensitive toward the orientation of the NH_2 group, only eclipsed forms were considered in the least-squares analysis of the experimental intensities. From the calculated relative free energies in Table 1, ratios of mole fractions between nonplanar and planar conformers of 69/31 (B3LYP) and 88/12 (MP2) are derived. The conformational composition predicted by the B3LYP method is in agreement with the experimental result (68(11)/32(11)% and $\Delta G^\circ = 0.6(3)$ kcal/mol), whereas the MP2 method overestimates the contribution of the nonplanar forms. In the prevailing nonplanar conformer, the S−N bond is bent toward the methyl group in ortho position (ϕ(C2−C1−S−N) = 64.3°). This can be rationalized by steric repulsion between the methyl group and the O1 atom (Figure 1b). The existence of a stable planar conformer in this ortho-substituted derivative is surprising, since such structures correspond to transition states in the parent and para-substituted benzenesulfonamide. We are unable to present a convincing explanation for the existence of this conformer in the gas phase. Apparently, the staggered orientation of the SO_2 group relative to the *o*-methyl group stabilizes this structure. The hydrogen bonds O···H and N···H also have not been excluded. In the crystal, only a nonplanar structure is present.[8] Similar to those for 4-MBSA, the calculations for 2-MBSA predict the structural parameters, excluding S═O and S−N bond lengths, and the vibrational amplitudes rather well.

Comparison of the molecular structures in the gas and in the solid phase reveals differences in the orientation of the S−N bond and NH_2 group. The gas phase consists of a mixture of eclipsed and staggered conformers with the eclipsed form prevailing. The preference of the eclipsed conformer in gaseous benzenesulfonamide has been rationalized by *intra*molecular hydrogen bonds between hydrogen and oxygen atoms of the SO_2NH_2 group (the H···O distance is about 2.5 Å).[3] On the other hand, only the staggered conformer exists in the crystal.[6−8] Short distances (1.85−2.12 Å) between O atoms of the SO_2 group and H atoms of the NH_2 group of a neighboring molecule indicate the existence of strong *inter*molecular N−H···O hydrogen bonds. These bonds stabilize the staggered conformation, which is also favored by steric reasons. The strong *inter*molecular hydrogen bonds in the crystal affect the parameters of the SNH_2 fragment. As a result, this fragment in the crystal is flattened and the S−N bond is significantly shorter (by about 0.07 Å) in comparison to that of the free molecule. The C−S−N angle is larger by about 4° in the crystal. The S−N bond in the crystal is nearly perpendicular to the benzene ring (C−C−S−N = 72° for para- and 78° for ortho-conformer). The C−C and C−S bond lengths in the crystal and in the gas phase are in good agreement with each other.

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Supporting Information Available: Experimental and calculated molecular intensities sM(s) and residuals for 2-MBSA (Figure S1). Experimental and calculated vibrational amplitudes and vibrational corrections for the staggered conformer of 4-MBSA (Table S1) and for the planar eclipsed form of 2-MBSA (Table S2). This material is available free of charge via the Internet at http://pubs.acs.org.

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