Steric Hindrance in a Cis-Trisubstituted Cyclopropane Derivative. Molecular Structure of 1-Chloro-1-phenylsulfonyl-2,3-dimethylcyclopropane

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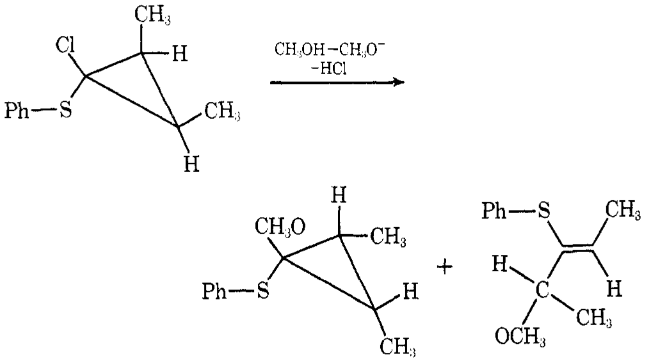
The methanolysis of 1-chloro-1-phenylmercapto-2,3-dimethylcyclopropane suggested the presence of a cyclopropyl cation as intermediate. Since the configuration of the reagent was unknown, it was oxidized to yield the sulfone and the crystals of triclinic space group $P\bar{1}$ were investigated by X-ray analysis. The structure was solved by the heavy atom method and refined to $R = 5.7\%$. The geometry of the cyclopropyl residue exhibits several features characteristic for these structures such as shortening of endocyclic C–C and exocyclic C–Cl, C–S, C–C bond distances. There is considerable steric hindrance between the cis substituents of the cyclopropyl residue, and the conformation about the S–C(1) bond is such that O(2) is "above" the triangle.

When 1-chloro-1-phenylmercapto-2,3-dimethylcyclopropane was subjected to methanolysis, a cyclic and an open chain reaction product was obtained. This finding was interpreted on the assumption that due to the stabilizing +M effect of the sulfur atom a cyclopropyl cation was present as a reaction intermediate.[1] The knowledge of the configuration of 1-chloro-1-phenylmercapto-2,3-dimethylcyclopropane was essential for the deduction of the reaction mechanism. However, the structure of the liquid reagent could not be established unambiguously by chemical or spectroscopic means and so it was oxidized to yield the crystalline 1-chloro-1-phenylsulfonyl-2,3-dimethylcyclopropane (I) and investigated in the X-ray structural analysis described below.



Materials and Methods.—We obtained I from U. Schöllkopf and P. Tonne in the form of stout plates crystallized from decalin (mp 93°). The crystallographic data presented in Table I were gathered from photographic and diffractometer measurements. The 2110 intensity data were collected by H. A. Paulus (Darmstadt) on an automatic STOE four-circle diffractometer using graphite monochromatized Mo radiation. The data were corrected for the usual geometrical factors and for the extra polarization caused by the monochromator[2] ($2\theta_M = 12°$). Due to the smallness of the crystal and of the linear absorption coefficient an absorption or extinction correction was deemed unnecessary.

TABLE I

CRYSTALLOGRAPHIC DATA

Space group triclinic, $P\bar{1}$

$a = 7.891 \pm 0.002$ Å $\alpha = 91.23 \pm 0.02°$

$b = 10.608 \pm 0.003$ Å $\beta = 111.29 \pm 0.02°$

$c = 7.801 \pm 0.002$ Å $\gamma = 100.81 \pm 0.02°$

Chemical formula, $C_{11}H_{13}ClO_2S$

Molecular weight, 244.75

Density observed (flotation in KI–H_2O), 1.354 g/cm^3

Density calculated (with $Z = 2$), 1.366 g/cm^3

Linear absorption coefficient (Mo), $\mu = 4.7$ cm^{-1}

Dimensions of crystal, 0.2 × 0.1 × 0.4 mm

From these data we calculated normalized structure factors (E's).[3] The mean $\langle E \rangle$ of 0.80 and mean $\langle E^2 - 1 \rangle$ of 0.93 suggested a centrosymmetric structure as did the distribution of E magnitudes.[4] A sharpened, origin-reduced Patterson map was prepared with ($E^2 - 0.95$) as coefficients, from which we could determine the locations of the "heavy" atoms S and Cl. A minimum function superposition[5] based on these atomic positions and their inversion-related mates revealed all atoms except phenyl ring carbon atoms C(9) and C(10) which could be found in a subsequent Fourier synthesis. A structure factor calculation based on positions for all nonhydrogen atoms from the electron density map and isotropic temperature ($B = 3.8$ Å^2) and a scale factor from a Wilson[6] plot yielded a reliability index $R = \Sigma||F_o| - |F_c||/\Sigma|F_o| = 0.28$. Full matrix least-squares refinement[7] of coordinates, scale, and isotropic temperature factors reduced R to 0.113.

In the course of the refinement the quantity minimized was $\Sigma W_{F_o}(|F_o| - |F_c|)^2$ where W_{F_o} means a weight to consider random and determinate errors of counting;[8] 252 reflections with $F_o < 3/\sqrt{W_{F_o}}$ were treated as unobserved.[8]

All hydrogen atoms could be found at heights 0.19–0.34 e/Å^3 in a difference electron density map following refinement with anisotropic temperature factors to $R = 0.072$. Refinement until shifts were less than $^1/_3$ the estimated standard deviations for all parameters including hydrogen atoms with fixed isotropic temperature factors (those of the covalently attached nonhydrogen atoms) lowered R to 0.057 for all 2110 reflections and left residuals no higher than 0.12 e/Å^3 in a difference Fourier synthesis.

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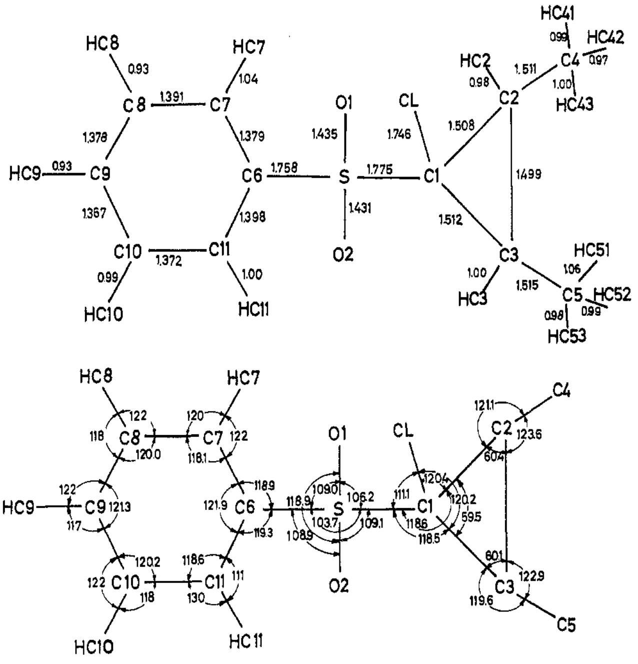

Figure 1.—Intramolecular distances and angles. The estimated standard deviations σ are 0.003 Å for distances involving S and Cl and 0.005 Å and 0.3°, respectively, for other data not involving hydrogen atoms. Distances and angles involving hydrogen atoms are accurate to about 0.05 Å and 5°, respectively. Due to the smallness of the anisotropic thermal parameters, the bond distances were not corrected for vibration effects. The bond angles C-C-HC(2) and C-C-HC(3) are 114 ± 2° while in the methyl groups bond angles C-C-H and H-C-H are 112 ± 3 and 108 ± 5°, respectively.

Results and Discussion

The final atomic parameters and the observed and calculated structure factors have been deposited with the ACS microfilm edition,[9] together with a stereoview of the packing of the molecules within the unit cell. In Figure 1 we have presented intramolecular bond distances and angles (the standard deviations are described in the legend) and in Tables II and III we have collected some least-squares planes through parts of the molecule and dihedral angles which were necessary to describe its conformation. Figure 2 shows a stereoview of a molecule when looking down b^*.

The six carbon atoms comprising the phenyl ring and the sulfur atom are nearly coplanar (Table II). The aromatic C–C bond distances should be about 1.394 Å,[10] but they are in the range from 1.367 to 1.398 Å (Figure 1) which might be due to steric and packing effects.

The C–C bond distances in the cyclopropyl residue of I are considerably shorter than paraffinic C–C single bonds (Table IV) and the C–C–C angles are close to 60°. Similar results have been predicted from theoretical consideration[11–13] and were obtained experimentally.[14–17]

TABLE II

SOME LEAST-SQUARES PLANES IN THE FORM
$pX + qY + rZ + s = 0$[a,b]

	Plane coefficients	Atoms	Deviations of atoms from the plane
a	$p = -0.1947$	C(6) +	0.001
	$q = -0.5018$	C(7) +	0.004
	$r = 0.8428$	C(8) +	−0.007
	$s = -0.2975$	C(9) +	0.003
		C(10) +	0.002
		C(11) +	−0.004
		S	−0.016
b	$p = 0.3099$	C(1) +	0.0
	$q = 0.6857$	C(2) +	0.0
	$r = 0.6586$	C(3) +	0.0
	$s = -1.4660$	Cl	1.421
		C(4)	1.185
		C(5)	1.211
		S	−1.482
		HC(2)	−0.867
		HC(3)	−0.871
		O(1)	−2.573
c	$p = -0.9485$	Cl +	0.0
	$q = 0.2704$	C(1) +	0.0
	$r = -0.1648$	S +	0.0
	$s = -2.3019$	C(2)	0.742
		C(3)	−0.757
		C(4)	1.577
		C(5)	−1.580
		HC(2)	1.128
		HC(3)	−1.203
		O(1)	0.067
		O(2)	−1.088

[a] X, Y, Z are the atomic coordinates in Å transformed into an orthogonal system with X perpendicular to b^* and c, Y along b^*, and Z along c. Atoms which define the planes are marked +. [b] The angles between the normals to the planes are $<a,b = 16$, $<a,c = 95$, $<b,c = 90°$.

TABLE III

DIHEDRAL ANGLES[a]

$$\begin{array}{ccc} & B\text{—}C & \\ / & & \backslash \\ A & & D \end{array}$$

Angle	Deg	Angle	Deg
Cl-C(1)-C(2)-C(3)	109.4	O(1)-S-C(1)-C(2)	−31.3
Cl-C(1)-C(3)-C(2)	−109.7	O(1)-S-C(1)-C(3)	37.5
Cl-C(1)-C(2)-C(4)	4.3	O(1)-S-C(6)-C(7)	−36.2
Cl-C(1)-C(3)-C(5)	−3.4	O(2)-S-C(6)-C(7)	−167.3
C(4)-C(2)-C(3)-C(1)	109.6	C(1)-S-C(6)-C(7)	103.4
C(5)-C(3)-C(1)-C(2)	−108.0	S-C(1)-C(2)-C(3)	−108.0
C(4)-C(2)-C(3)-C(5)	1.7	S-C(1)-C(3)-C(2)	108.3
HC(2)-C(2)-C(3)-HC(3)	−1.2	S-C(1)-C(2)-C(4)	138.4
S-C(1)-C(2)-HC(2)	3.7	S-C(1)-C(3)-C(5)	−138.6
S-C(1)-C(3)-HC(3)	−0.6	Cl-C(1)-C(2)-HC(2)	−146.3
O(1)-S-C(1)-Cl	−177.2	Cl-C(1)-C(3)-HC(3)	142.6
O(2)-S-C(1)-Cl	−53.6		

[a] These four-atom angles are defined as zero when, looking along B → C bond B → A is parallel to bond C → D and is counted positive when C → D is rotated clockwise with respect to B → A.

In Table IV the exocyclic C(1)–Cl, C(1)–S, C(2)–C(4), and C(3)–C(5) bond distances are compared with data for the corresponding single and double bonds.

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(9) Listings of structure factors, coordinates, and anisotropic temperature factors will appear following these pages in the microfilm edition of this volume of the journal. Single copies may be obtained from the Reprint Department, ACS Publications, 1155 Sixteenth St., N.W., Washington, D. C. 20036, by referring to author, title of article, volume, and page number. Remit check or money order for $3.00 for photocopy or $2.00 for microfiche.

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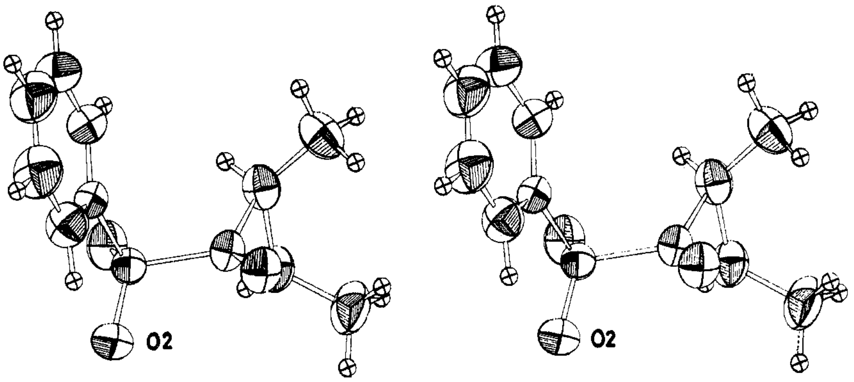

Figure 2.—A stereo plot of one molecule viewed down b^* with the 50% thermal ellipsoids: C. K. Johnson, Oak Ridge National Laboratory Report BRNL-3794, Oak Ridge, Tenn., 1965.

TABLE IV

COMPARISON OF BOND DISTANCES (IN Å) FROM THIS STRUCTURE WITH AVERAGED DATA FOR CORRESPONDING LENGTHS INVOLVING SINGLY AND DOUBLY BONDED CARBON ATOMS[a]

Data in this structure for	Averaged data	
C–Cl = 1.746	R–C–Cl = 1.767 ± 0.005	R═C—Cl = 1.719 ± 0·005
C–CH_3 = 1.511	R–C–CH_3 = 1.537 ± 0.005	R═C—CH_3 = 1.510 ± 0.005
C(1)–SO_2 = 1.775	R–C–SO_2 = 1.80 ± 0.01	
$C_6H_5SO_2$ = 1.758		$C_6H_5SO_2$ = 1.753 ± 0.002[b]
C(1)–C(2) C(1)–C(3) = 1.510	C–C aliph = 1.537 ± 0.005	>C═C< olefin = 1.335 ± 0.005
C(2)–C(3) = 1.499		
C–C arom = 1.367–1.398		C–C arom = 1.394 ± 0.005

[a] See ref 9. [b] See ref 22.

The bond lengths in I are between the values given in Table IV and suggest the "olefinic"[18] character of the cyclopropyl residue as do the exocyclic angles which according to the above-cited theoretical and experimental publications should be about 116° for C–C–H and about 118° for C–C–X; the angles S–C(1)–C(2), S–C(1)–C(3), and the C–C–HC(2) and C–C–HC(3) angles are close to these values. However, the angles C–C–X where X stands for the chlorine atom or the methyl groups, which are cis to each other, are significantly (7–15σ) greater than 118° and one must conclude that between these groups steric hindrance occurs. This finding is supported by the observation that the angles C(2)–C(3)–C(5) and C(3)–C(2)–C(4) are increased by 3° compared to the angles C(1)–C(3)–C(5) and C(1)–C(2)–C(4) (Figure 1) which can be interpreted in terms of the greater van der Waals[20] radius of the methyl group (2.0 Å) with respect to the chlorine atom (1.8 Å). Another indication for steric hindrance are the interatomic, nonbonded distances Cl–C(4), 3.173 Å, Cl–C(5), 3.145 Å, C(4)–C(5), 3.029 Å, which all are smaller than the corresponding sum of the van der Waals radii, 3.8 Å for Cl–CH_3 and 4 Å for CH_3–CH_3, respectively.

It must be due to the symmetry of the cyclopropyl residue—the plane Cl–C(1)–S acts as a pseudo mirror plane (Table II)—that in spite of the just mentioned steric hindrance its substituents are truly cis to each other; *i.e.*, in the four-atom planes Cl, C(1), C(2), C(4); Cl, C(1), C(3), C(5); C(4), C(2), C(3), C(5) the atoms are coplanar with maximum discrepancies of 0.02 Å; the angles between the normals to these planes are about 70°.

The angle Cl–C(1)–S of 111.1° is smaller than the expected value of 116–118°. A similar angle was found for Cl–C–Cl (114°) in 1,1-dichlorocyclopropane[17] and for O–C–O (110°) in benzocyclopropapyran.[21]

Bond angles and distances of the sulfonyl group compare well with data obtained for saccharine derivatives[22,23] and for *N*-methyl-2-methylsulfonyl-2-phenylsulfonylvinylideneamine.[24]

The conformation of I is such that the S–O(2) bond is almost coplanar with the phenyl ring [Table III; the O(2)–S–C(6)–C(7) dihedral angle is only 13°] while the S–O(1) bond is almost cis planar with the cyclopropyl residue; *i.e.*, the projection of the S–O(1) bond along the S–C(1) direction bisects the cyclopropyl triangle (Figure 2, Table III). As a consequence of this conformation the planes through phenyl and cyclopropyl residues are almost parallel to each other with an angle of only 17° between the normals to these planes.

The S–O part of a sulfonyl group can be compared to a carbonyl C–O group. It is striking that several cyclopropane derivatives with an α-carbonyl group which have been studied by electron diffraction and X-ray crystallography all exhibit a conformation similar to I: the carbonyl or S–O group, respectively,

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[18] We have called the cyclopropyl residue "olefinic" referring to the π-electron picture proposed by Walsh[13] and to its chemical properties reviewed by Pete.[19]

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is cis to the cyclopropyl residue; *i.e.*, the oxygen atom is "above" the triangle. From the substances investigated by electron diffraction (cyclopropanecarboxylic acid chloride, cyclopropyl methyl ketone,[25] and cyclopropylcarboxaldehyde[26]) only average C–C distances were obtained, whereas the X-ray data for cyclopropanecarbohydrazide[27] and cyclopropanecarboxamide[28] yielded an asymmetry in the cyclopropyl residue; the C–C bond opposite the carbonyl group [*i.e.*, C(2)–C(3)] was found to be significantly (3.5 σ) smaller than the other two C–C bonds in the cyclopropyl ring which is also true (3 σ) for I, Figure 1. That the C(2)–C(3) bond distance in I is not so short as in the above two cyclopropane derivatives might be due to the steric hindrance between the C(4) and C(5) methyl groups discussed earlier.

Within the crystal structure the molecules are arranged such that the methyl groups come together in a region parallel to the a,b plane at $c = {}^1/_2$ and the phenyl rings are not stacked but alternately packed around the a,b plane in $c = 0$.

The intermolecular distances are all equal to or greater than the sums of the corresponding van der Waals radii. Relatively close contacts occur between the chlorine atoms, 3.378 Å, and between O(1) and HC(7), 2.506 Å.

The calculations were performed on a UNIVAC 1108 computer of the Gesellschaft für wissenschaftliche Datenverarbeitung mbH, Göttingen. The ORTEP plots were carried out at Deutsches Rechenzentrum, Darmstadt.

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The Condensation of Succinic Anhydrides with Schiff Bases. Scope and Mechanism[1a]

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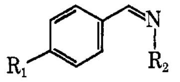
The condensation of a series of para-substituted benzylidenecyclohexylamines with succinic anhydride to yield the corresponding *trans*- and *cis*-1-cyclohexyl-4-carboxy-5-aryl-2-pyrrolidinones has been studied. The reactivities of the Schiff bases have been shown to increase with the increasing electron-donating ability of substituents, an order of reactivity opposite to that expected for a Perkin-type mechanism. Indirect evidence supporting a reaction sequence involving iminolysis of *gem*-dimethylsuccinic anhydride followed by rearrangement of the iminolysis adduct is also presented.

In a recent publication[2] we described the condensation of benzylidenemethylamine **1a** with succinic anhydride to yield *trans*- and *cis*-1-methyl-4-carboxy-5-phenyl-2-pyrrolidinone (**2a** and **3a**, respectively). In order to examine the mechanism of this reaction and concomitantly to extend its synthetic utility to the preparation of substituted 5-aryl-2-pyrrolidinones of interest as precursors to nicotine analogs,[3] we have studied the condensation of the para-substituted benzylidenecyclohexylamines **1b–f** with succinic anhydride. With the exception of the para nitro compound **1f**, which resisted reaction, each Schiff base yielded a diastereomeric mixture of pyrrolidinones which could be separated into the trans and cis isomers **2** and **3**, respectively. The cis acids **3b** and **3c** were characterized as their methyl esters **3b′** and **3c′**, respectively.

As previously shown,[2] stereochemical assignments in each case could be made on the basis of the magnitude of the coupling constant for the C-5 methine proton, which for the cis isomers is 9 Hz and for the trans isomers 2–5 Hz. Since the nmr signals for the methoxycarbonyl protons in the corresponding cis methyl esters appear about 0.4–0.5 ppm upfield from the trans esters,[2] it was possible to estimate the relative yields of the diastereomers by integration of the nmr spectra of the



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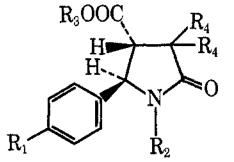

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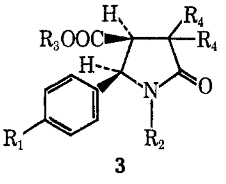

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Compd	R_1	R_2	R_3	R_4
a	H	CH_3	H	H
b	$(CH_3)_2N$	C_6H_{11}	H	H
b′	$(CH_3)_2N$	C_6H_{11}	CH_3	H
c	CH_3O	C_6H_{11}	H	H
c′	CH_3O	C_6H_{11}	CH_3	H
d	H	C_6H_{11}	H	H
e	Cl	C_6H_{11}	H	H
f	NO_2	C_6H_{11}	H	H
g	CH_3O	C_6H_{11}	H	CH_3
g′	CH_3O	C_6H_{11}	CH_3	CH_3

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