Folded Conformations. Part VII.[1,2] Crystal and Molecular Structure of *NN'*-[Bis-(α-tosylbenzyl)]urea Acetone Solvate. Comparison between Solution and Solid-state Conformation

By **Rense M. Tel** and **Jan B. F. N. Engberts,*** Department of Organic Chemistry, University of Groningen, Zernikelaan, Groningen, The Netherlands

The crystal and molecular structure at −160 °C of the title compound has been determined by direct methods from diffractometer data. Crystals are monoclinic, $a = 10.869(10)$, $b = 22.741(21)$, $c = 13.124(6)$ Å, $\beta = 110.22°(6)$, space group $P2_1/c$, $Z = 4$. The structure was refined by anisotropic least-squares to R 0.088 for 4 085 independent reflections. The molecule resides in a folded conformation in which the hydrogen atoms attached to both nitrogen atoms are hydrogen bonded to one molecule of acetone of crystallization. The conformation is similar to that favoured in solution, although in the latter the position of acetone is uncertain. On the basis of empirical potential-energy calculations, we suggest that conformational preferences are caused by non-bonded repulsive interactions.

THE results of our recent n.m.r. studies of *NN'*-[bis-(α-tosylbenzyl)]urea [1] (1), $[p\text{-MeC}_6\text{H}_4\text{SO}_2\text{CH(Ph)NH}]_2\text{C:O}$, have led us to suggest that (1) adopts in solution a favoured folded conformation in which the methyl protons are facing the plane of the most remote phenyl ring of the benzyl moiety and in which the methine protons are positioned above (or below) the plane of the most remote tosyl aromatic ring.[1] It was suggested that intramolecular dipolar interactions involving the polarized S–O bonds and the dipole of the urea moiety played a major role in determining the conformational preference.[1,3,4] We have now carried out an *X*-ray crystallographic study of the crystal and molecular structure of (1) in order to establish whether the molecule also prefers the folded conformation in the solid state,† and also in order to carry out empirical potential-energy calculations which could shed light on the intramolecular interactions in a more quantitative way.

For many compounds solution and solid-state conformations are similar,[2,5-7] but this is by no means a

---

† The crystal (1) contains one molecule of acetone of crystallization (ref. 1).

[1] Part VI, R. M. Tel and J. B. F. N. Engberts, *Rec. Trav. chim.*, 1974, **93**, 37.

[2] Part V, I. J. Tickle and J. B. F. N. Engberts, *J.C.S. Perkin II*, 1973, **2031**, and references therein.

[3] G. Jeminet, C. Pigenet, and H. Lumbroso, *Bull. Soc. chim. France*, **1966**, 3631.

[4] S. van der Werf and J. B. F. N. Engberts, *Rec. Trav. chim.*, 1970, **89**, 423; R. van Est-Stammer, Ph.D. Thesis, University of Groningen, 1973.

[5] K. D. Kopple and D. H. Marr, *J. Amer. Chem. Soc.*, 1967, **89**, 6193.

[6] L. E. Webb and Chi-Fan Lin, *J. Amer. Chem. Soc.*, 1971, **93**, 3818.

[7] G. Lepora, S. Migdal, D. E. Blagdon, and M. Goodman, *J. Org. Chem.*, 1973, **38**, 2590.

general rule.[8-10] The relation between the two is of major interest in protein structural chemistry.[11]

EXPERIMENTAL

Compound (1) was prepared by a known procedure.[12] It was recrystallised quickly from acetone <45 °C, because of its instability. Slow cooling of the solution to −20 °C provided suitable crystals. Initial cell dimensions at room temperature were determined from zero-layer Weissenberg photographs.[13] Since the diffractometer experiment would be carried out at low temperature (owing to crystal instability) a zero-layer Weissenberg photograph was also obtained with the crystal cooled to −160 °C by a stream of cold nitrogen gas obtained by evaporation of liquid nitrogen. Comparison of this photograph with that obtained at room temperature indicated the absence of any phase transition. Accurate cell dimensions were obtained by least-squares adjustments to the θ, χ, and ϕ values of six reflections, observed on a three-circle diffractometer.

Crystal Data (*at* −160 °C).—$C_{32}H_{34}N_2O_6S_2$, $M = 606.8$. Monoclinic prismatic, $a = 10.869(10)$, $b = 22.741(21)$, $c = 13.124(6)$ Å, $\beta = 110.22(6)$,° $U = 3\,044.0$ Å^3 $D_m = 1.28$ (20 °C), $Z = 4$, $D_c = 1.32$. Space group $P2_1/c$. Mo-K_α radiation $\lambda = 0.71069$ Å; μ(Mo-K_α) = 2.45 cm^{-1}.

A crystal with dimensions 0.3 × 0.3 × 0.3 mm was cooled to −160 °C by a stream of cold nitrogen gas using a special cooling system,[14] and intensities obtained on a three-circle automatic Nonius-diffractometer with zirconium-filtered molybdenum radiation by the θ—2θ integrating scan technique. The b axis was rotated parallel to ϕ.

All independent reflections with $\theta \leqslant 28.1°$ were measured. Every 20 reflections a chosen reference reflection (214) was measured, and the deviations in intensity of this reflection from the mean found to be <5%, except for one value of *ca.* 10%.

Corrections for the Lorentz and polarization effects were applied. No correction for absorption was made due to the small value of the absorption coefficient and the small variation in the pathlength through the crystal. Reflections with net negative intensity were rejected; for other reflections the weight, w_c, was obtained as $w_c = |\sigma_c(F)|^{-2}$ where $\sigma_c(F)$ is the standard deviation in F from counting statistics taking filter-factor errors into account. For the structure determination 5 939 independent reflections were used.

The structure elucidation was carried out with aid of an updated version of the '*X*-Ray' system of crystallographic programs.[15] Calculations were performed at the University Computing Centre with a CDC 74 16 computer.

The structure was determined by direct methods. After calculation of the E values, 326 reflections ($E > 1.8$) were used for the program Multan.[15] From 16 sets of signs an E map was calculated for the set having the highest figures of merit. The maxima corresponding with nearly all non-hydrogen atoms could be located by means of a peak search program.[15]

The atomic parameters of the non-hydrogen atoms were anisotropically refined by a least-squares program, using scattering factors from ref. 16; for hydrogen those from ref. 17 were used. In the refinement procedure the weight, $w = [w_c^{-1} + P^2F^2 + J\sin\theta]^{-1}$, was used, in which $P^2 = 28 \times 10^{-4}$ and $J = 0.3$.

All hydrogen atoms were then located from a difference-Fourier synthesis, from which were eliminated 1 669 reflections having intensity $I < 3\sigma(I)$ and 185 reflections with F_o differing from F_c by >50%.

Keeping the refined bond angles unchanged, the hydrogen positions were adjusted to make the C–H and N–H bond lengths 1.08 and 0.90 Å. The index R decreased to 0.088, and the weighted index R' to 0.147. Inclusion of the 185 weak reflections did not alter the values of the co-ordinates and thermal parameters but changed R to 0.103, and R' to 0.185.

TABLE 1

Fractional atomic co-ordinates and thermal parameters * with standard deviations in parentheses; hydrogen atoms are numbered according to the carbon atoms to which they are attached. The charges on the atoms, used in the program WMIN are also given

	x/a	y/b	z/c	q
S(01)	0.2709(1)	0.2329(1)	−0.0373(1)	0.36
S(02)	0.2365(2)	−0.0715(1)	0.0272(1)	0.36
O(01)	0.1667(4)	0.2495(2)	0.0014(4)	−0.26
O(02)	0.2966(4)	0.2693(2)	−0.1183(3)	−0.26
O(03)	0.4065(4)	0.0642(2)	−0.0294(3)	−0.32
O(04)	0.1188(5)	−0.0574(2)	0.0508(4)	−0.26
O(05)	0.2848(5)	−0.1312(2)	0.0410(4)	−0.26
O(06)	0.1496(5)	0.1068(2)	0.1780(4)	−0.24
N(01)	0.2414(5)	0.1191(2)	−0.0053(4)	0.11
N(02)	0.3162(5)	0.0364(2)	0.0983(4)	0.11
C(01)	0.7712(8)	0.2206(4)	0.3544(5)	0.01
C(02)	0.6497(6)	0.2214(3)	0.2570(5)	0.03
C(03)	0.6498(6)	0.2293(3)	0.1510(5)	−0.09
C(04)	0.5381(6)	0.2309(3)	0.0621(5)	0.03
C(05)	0.4167(6)	0.2262(2)	0.0769(5)	−0.06
C(06)	0.4104(6)	0.2180(3)	0.1791(5)	0.03
C(07)	0.5266(7)	0.2159(3)	0.2681(5)	−0.09
C(08)	0.2416(6)	0.1585(2)	−0.0915(4)	−0.02
C(09)	0.1162(6)	0.1582(2)	−0.1885(5)	0.02
C(10)	0.1196(6)	0.1655(3)	−0.2934(5)	−0.09
C(11)	0.0054(7)	0.1638(3)	−0.3840(5)	−0.04
C(12)	−0.1151(7)	0.1532(3)	−0.3711(5)	−0.06
C(13)	−0.1210(7)	0.1459(3)	−0.2662(5)	−0.04
C(14)	−0.0055(6)	0.1492(3)	−0.1767(4)	−0.09
C(15)	0.3272(6)	0.0722(2)	0.0184(4)	0.12
C(16)	0.3680(6)	−0.0228(2)	0.1112(5)	−0.02
C(17)	0.4117(6)	−0.0457(3)	0.2272(4)	0.02
C(18)	0.3635(7)	−0.0235(3)	0.3052(5)	−0.09
C(19)	0.4029(7)	−0.0494(3)	0.4084(5)	−0.04
C(20)	0.4872(7)	−0.0963(3)	0.4322(5)	−0.06
C(21)	0.5385(7)	−0.1175(3)	0.3569(6)	−0.04
C(22)	0.4991(7)	−0.0923(3)	0.2538(5)	−0.09
C(23)	0.2118(6)	−0.0478(2)	−0.1077(4)	−0.06
C(24)	0.2986(6)	−0.0690(3)	−0.1554(5)	0.03
C(25)	0.2855(7)	−0.0476(3)	−0.2600(5)	−0.09
C(26)	0.1868(7)	−0.0076(3)	−0.3136(5)	0.03
C(27)	0.1023(6)	0.0120(3)	−0.2614(5)	−0.09
C(28)	0.1154(6)	−0.0090(2)	−0.1572(5)	0.03
C(29)	0.1761(8)	0.0168(3)	−0.4240(5)	0.01
C(30)	0.0065(7)	0.1851(3)	0.1759(6)	−0.06
C(31)	0.0876(6)	0.1332(3)	0.2272(5)	0.26
C(32)	0.0919(8)	0.1151(3)	0.3373(6)	−0.06

---

[8] R. Carruthers, F. M. Dean, L. E. Houghton, and A. Ledwith, *Chem. Comm.*, 1967, 1206.

[9] C. K. Prout and E. E. Castellano, *J. Chem. Soc.* (*A*), 1970, 2775.

[10] A. E. Tonelli, and A. J. Brewster, *J. Amer. Chem. Soc.*, 1972, **94**, 2851.

[11] J. Drenth, *Proc. Fed. European Biochem. Socs.*, 1972, **29**, 1.

[12] H. Meyer, R. M. Tel, J. Strating, and J. B. F. N. Engberts, *Rec. Trav. chim.*, 1973, **92**, 72.

[13] H. van der Wal, unpublished results.

[14] F. van Bolhuis, *J. Appl. Cryst.*, 1971, **4**, 263.

[15] J. M. Stewart, G. J. Kruger, H. L. Ammon, G. Dickinson, and S. R. Hall, '*X*-Ray System' of Crystallographic Programs, University of Maryland Technical Report, TR 192, 1972.

[16] D. T. Cromer and J. B. Mann, *Acta Cryst.*, 1968, **A24**, 321.

[17] R. F. Stewart, E. R. Davidson, and W. T. Simpson, *J. Chem. Phys.*, 1965, **42**, 3175.

TABLE 1 (*Continued*)

	x/a	y/b	z/c	q
H(101)	0.211	0.129	0.055	0.07
H(201)	0.266	0.046	0.138	0.07
H(011)	0.741	0.241	0.414	0.01
H(012)	0.841	0.251	0.354	0.01
H(013)	0.801	0.181	0.384	0.01
H(03)	0.740	0.229	0.141	0.06
H(04)	0.538	0.231	−0.018	0.05
H(06)	0.320	0.218	0.189	0.05
H(07)	0.517	0.206	0.348	0.06
H(08)	0.322	0.149	−0.122	0.01
H(10)	0.210	0.176	−0.303	0.06
H(11)	0.005	0.174	−0.464	0.05
H(12)	−0.205	0.153	−0.441	0.05
H(13)	0.211	0.136	−0.256	0.05
H(14)	−0.016	0.139	−0.097	0.06
H(16)	0.438	−0.023	0.071	0.01
H(18)	0.294	0.017	0.285	0.06
H(19)	0.363	−0.029	0.468	0.05
H(20)	0.517	−0.116	0.512	0.05
H(21)	0.609	−0.158	0.377	0.05
H(22)	0.539	−0.112	0.194	0.06
H(24)	0.379	−0.099	−0.115	0.05
H(25)	0.356	−0.068	−0.300	0.06
H(27)	0.022	0.042	−0.301	0.06
H(28)	0.055	0.011	−0.117	0.05
H(291)	0.146	−0.013	−0.484	0.01
H(292)	0.276	0.027	−0.424	0.01
H(293)	0.106	0.057	−0.454	0.01
H(301)	−0.094	0.165	0.136	0.02
H(302)	0.037	0.195	0.106	0.02
H(303)	0.027	0.215	0.246	0.02
H(321)	0.002	0.105	0.347	0.02
H(322)	0.142	0.075	0.367	0.02
H(323)	0.130	0.140	0.400	0.02

Final co-ordinates and standard deviations as calculated by the least-squares program [13] are given in Table 1. The relatively high standard deviations and thermal parameters (see Supplementary Publication) originate most probably from thermal motion in the molecule. The results of a rigid-body analysis [18,19] of the thermal motion of the molecule strongly support this conclusion.

The co-ordinates listed in Table 1 were used in the program WMIN,[20] which calculates the potential energy due to non-bonded interactions using equation (1). The repulsive

$$E_{\text{nb}} = (A_i + A_j)\exp[(A_i + A_j - R_{ij})/(B_i + B_j)] - C_iC_j/R_{ij}^6 + 332.17q_iq_j/R_{ij} \quad (1)$$

forces are represented in the first term. The attractive interactions (van der Waals) and the Coulomb interactions are given by the second and third term, respectively. The constants A, B, and C were taken from ref. 21 for carbon and hydrogen, from ref. 22 for sulphur, from ref. 23 for oxygen, and from ref. 24 for nitrogen. These constants were adequately converted (as described previously [25]) before being used in equation (1). Values for the net-charges, q, on the respective atoms were taken from literature data for related molecules [26] and are listed in Table 1. Observed structure amplitudes and structure factors, calculated from the atomic parameters in Table 1, and thermal parameters are given in Supplementary Publication No. SUP 21587 (18 pp., 1 microfiche).*

TABLE 2

Distances (Å) and angles (deg.) within the molecule with standard deviations in parentheses

(a) Distances

S(01)–O(01)	1.444(5)	C(09)–C(10)	1.399(9)
S(01)–O(02)	1.449(5)	C(10)–C(11)	1.392(8)
S(02)–O(04)	1.452(6)	C(11)–C(12)	1.399(11)
S(02)–O(05)	1.443(5)	C(12)–C(13)	1.409(11)
S(01)–C(05)	1.771(6)	C(13)–C(14)	1.394(8)
S(01)–C(08)	1.821(6)	C(14)–C(09)	1.398(10)
S(02)–C(16)	1.844(6)	C(16)–C(17)	1.521(8)
S(02)–C(23)	1.779(6)	C(17)–C(18)	1.395(10)
O(03)–C(15)	1.243(8)	C(18)–C(19)	1.402(9)
O(06)–C(31)	1.239(9)	C(19)–C(20)	1.368(10)
N(01)–C(08)	1.443(8)	C(20)–C(21)	1.380(11)
N(01)–C(15)	1.379(7)	C(21)–C(22)	1.393(9)
N(02)–C(16)	1.447(7)	C(22)–C(17)	1.386(9)
N(02)–C(15)	1.364(8)	C(23)–C(24)	1.386(10)
C(01)–C(02)	1.487(8)	C(24)–C(25)	1.416(9)
C(02)–C(03)	1.403(10)	C(25)–C(26)	1.396(9)
C(03)–C(04)	1.363(8)	C(26)–C(27)	1.396(11)
C(04)–C(05)	1.402(10)	C(27)–C(28)	1.408(9)
C(05)–C(06)	1.379(9)	C(28)–C(23)	1.353(8)
C(06)–C(07)	1.394(8)	C(29)–C(26)	1.518(10)
C(07)–C(02)	1.401(11)	C(30)–C(31)	1.486(9)
C(08)–C(09)	1.510(7)	C(31)–C(32)	1.488(10)

(b) Angles

O(01)–S(01)–O(02)	118.9(3)	C(08)–C(09)–C(14)	121.3(6)
O(01)–S(01)–C(05)	107.8(3)	C(10)–C(09)–C(14)	118.3(5)
O(01)–S(01)–C(08)	109.1(3)	C(09)–C(10)–C(11)	121.2(7)
O(02)–S(01)–C(05)	109.1(3)	C(10)–C(11)–C(12)	119.8(6)
O(02)–S(01)–C(08)	107.3(3)	C(11)–C(12)–C(13)	120.0(5)
C(05)–S(01)–C(08)	103.6(2)	C(12)–C(13)–C(14)	119.0(7)
O(04)–S(02)–O(05)	119.4(3)	C(09)–C(14)–C(13)	121.7(6)
O(04)–S(02)–C(16)	107.3(3)	S(02)–C(16)–N(02)	107.4(4)
O(04)–S(02)–C(23)	107.7(3)	S(02)–C(16)–C(17)	107.6(4)
O(05)–S(02)–C(16)	108.4(3)	N(02)–C(16)–C(17)	114.1(5)
O(05)–S(02)–C(23)	109.4(3)	C(16)–C(17)–C(18)	123.0(5)
C(16)–S(02)–C(23)	103.4(3)	C(16)–C(17)–C(22)	117.6(6)
O(03)–C(15)–N(01)	122.1(5)	C(18)–C(17)–C(22)	119.4(6)
O(03)–C(15)–N(02)	124.1(5)	C(17)–C(18)–C(19)	119.3(6)
N(01)–C(15)–N(02)	113.8(6)	C(18)–C(19)–C(20)	120.3(7)
C(08)–N(01)–C(15)	118.2(6)	C(19)–C(20)–C(21)	121.0(6)
C(15)–N(02)–C(16)	120.8(6)	C(20)–C(21)–C(22)	119.1(6)
C(01)–C(02)–C(03)	123.3(7)	C(17)–C(22)–C(21)	120.9(7)
C(01)–C(02)–C(07)	120.4(6)	S(02)–C(23)–C(24)	116.9(4)
C(03)–C(02)–C(07)	116.3(5)	S(02)–C(23)–C(28)	120.0(5)
C(02)–C(03)–C(01)	123.1(7)	C(24)–C(23)–C(28)	123.0(6)
C(03)–C(04)–C(05)	118.8(6)	C(23)–C(24)–C(25)	117.6(6)
S(01)–C(05)–C(04)	119.1(5)	C(24)–C(25)–C(26)	120.9(7)
S(01)–C(05)–C(06)	120.3(5)	C(25)–C(26)–C(27)	118.8(6)
C(04)–C(05)–C(06)	120.7(5)	C(25)–C(26)–C(29)	120.7(7)
C(05)–C(06)–C(07)	119.0(7)	C(27)–C(26)–C(29)	120.4(6)
C(02)–C(07)–C(06)	122.1(6)	C(26)–C(27)–C(28)	120.4(5)
S(01)–C(08)–N(01)	108.5(4)	C(23)–C(28)–C(27)	119.3(6)
S(01)–C(08)–C(09)	108.6(4)	O(06)–C(31)–C(30)	119.6(6)
N(01)–C(08)–C(09)	114.4(5)	O(06)–C(31)–C(32)	122.2(6)
C(08)–C(09)–C(10)	120.4(6)	C(30)–C(31)–C(32)	118.3(6)

---

* For details see Notice to Authors No. 7, in *J.C.S. Perkin II*, 1974, Index issue.

[18] D. W. J. Cruickshank, *Acta Cryst.*, 1956, **9**, 754.

[19] G. S. Pawley, *Acta Cryst.*, 1963, **16**, 1204.

[20] W. R. Busing, *Acta Cryst.*, 1972, **A28**, Suppl. 4, *S* 252.

[21] D. E. Williams, *Trans. Amer. Cryst. Assocn.*, 1970, **6**, 21.

[23] S. Cerrini and G. S. Pawley, *Acta Cryst.*, 1973, **A29**, 660.

[23] V. G. Dashevskii, Yu. T. Struchkov, and Z. A. Akopyan, *Zhur. strukt. Khim.*, 1966, **7**, 594.

[24] U. Shmueli and I. Goldberg, *Acta Cryst.*, 1973, **B29**, 2466; T. Kuan, A. Warshel, and O. Schnepp, *J. Chem. Phys.*, 1970, **52**, 3012.

[25] C. P. Brock and J. A. Ibers, *Acta Cryst.*, 1973, **B29**, 2426.

[26] W. J. Hehre and J. A. Pople, *J. Amer. Chem. Soc.*, 1970, **92**, 2191; D. J. Bertelli and T. G. Andrews, *ibid.*, 1969, **91**, 5280; G. Robinet, F. Crasnier, J. F. Labarre, and C. Leibovici, *Theor. Chim. Acta*, 1972, **25**, 259; A. Julg and P. Carles, *ibid.*, 1963, **1**, 140; J. E. DelBene, G. T. Worth, F. T. Marchese, and M. E. Conrad, *ibid.*, 1975, **36**, 195; F. de Jong, Ph.D. Thesis, University of Groningen, 1972; M. Scholz, H. J. Köhler, and U. Ziegler, *J. prakt. Chemie*, 1974, **316**, 103; A. Ažman, M. Drofenik, D. Hadži, and B. Lukman, *J. Mol. Structure* 1968, **1**, 181.

RESULTS AND DISCUSSION

Table 2 lists interatomic distances and interbond angles in (1). One molecule is pictured in Figure 1, and Figure 2 gives a stereoscopic projection of the contents of the unit cell on the *ab* plane.

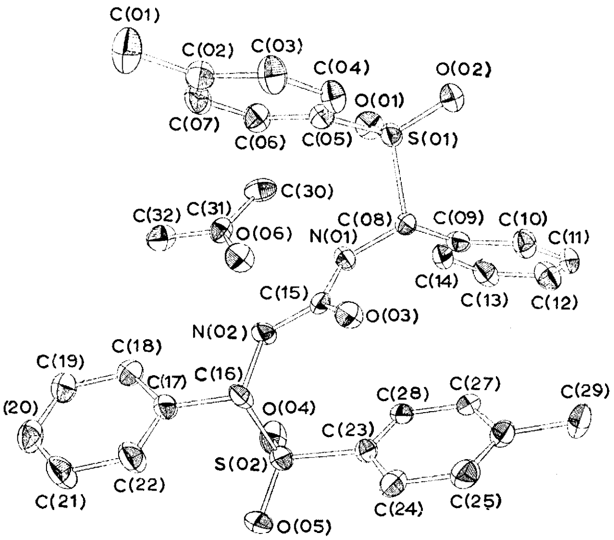


FIGURE 1 A view of the molecule; hydrogen atoms are not depicted

In both tosyl groups, the bisector of O–S–O is approximately parallel with the p_π orbitals of the adjacent aromatic ring. This situation is apparently favourable on the basis of conjugational interaction and has been encountered previously.[2] As a consequence, C–S lengths are somewhat longer than expected.[2]

Although the C–C(aromatic) bond lengths range from 1.353(8) to 1.416(9) Å, no pronounced quinonoid geometry is observed in the phenyl rings bearing a sulphonyl moiety. The mean C–C(aromatic) bond length is 1.392 Å.

The urea group is planar, as expected,[27-29] but the C–O bond length and N–C–N angle are smaller, and C–N and N–C–O greater than in other urea derivatives.[27-31] These differences in bond lengths may be attributed to the electron-withdrawing electronic effect of the sulphonyl group. Hydrogen bonding of the urea moiety to the acetone of crystallization may be invoked to explain the deviations of the bond angles. The urea hydrogen atoms H(101) and H(201) lie 0.354 and 0.125 Å, out of the N,CO,N plane; the carbon atoms C(08) and C(16) are 0.051 and 0.398 Å from this plane.

The heavy atoms of the acetone of crystallization also constitute a plane,[32] and the bond lengths and angles agree with literature values.[33,34] The angle between this plane and that of N,CO,N is 20.3°. Both urea hydrogen atoms are clearly hydrogen bonded to the oxygen atom of the acetone molecule.[35] The hydrogen bond lengths [H(101) · · · O(06) 2.020, and H(201) · · · O(06) 2.054 Å], are consistent with previously obtained values.[27,36] However the H(101) · · · O(06) · · · H(201) angle (63.9°) is much smaller than expected on the basis of two hydrogen bonds directed towards the two lone pairs contained in two separate orbitals on oxygen. Therefore one must assume that the urea hydrogen atoms interact with the broad half-moon shaped maximum of positive electron density extended in the acetone plane. An analogous situation has been encountered for oxalic acid dihydrate,[37] ammonium oxalate,[38] cyanuric acid,[39] and glycine.[40]

From Figure 1 it can be seen that (1) in the crystal is present in a folded conformation which is very similar to that suggested for (1) in solution. This result strongly suggests that the preference for the folded conformation in solution is not primarily due to a release of solvent molecules upon bending of the molecule. Since there is no close intermolecular approach in the crystal between separate molecules, it is likely that intramolecular interactions are principally responsible for the conformational preference. For the solution conformation the same conclusion has been drawn since the magnitude of the observed intramolecular shielding effects is hardly affected by changes in the concentration of (1). Thus, it appeared of interest to calculate the internal energy of the whole molecule in the crystal due to non-bonded and Coulombic interactions as a function of rotation around specific bonds by use of the program WMIN (see Experimental section).* Rotational angles corresponding to minima in E_{nb} are given in Table 3. A zero angle indicates that the energy minimum corresponds exactly with the conformation around that particular bond as found in the crystal. Table 3 shows that the conformation found for (1) in the crystal closely corresponds to a minimum in E_{nb}. This is also the case when the molecule of acetone of crystallization is omitted from the calculation,† but the energy minimum is then higher owing to a decrease in the attractive forces. The calculations further show that for all rotations examined, the contri-

---

* All 1,3 non-bonded interactions were subtracted from calculated values.

† The charges on the atoms were kept the same except for those on nitrogen and its protons; these were changed to 0.13 and 0.06.

[27] P. Vaughan and J. Donohue, *Acta Cryst.*, 1952, **5**, 530.

[28] J. E. Worsham, H. A. Levy, and S. W. Peterson, *Acta Cryst.*, 1957, **10**, 319.

[29] A. Caron and J. Donohue, *Acta Cryst.*, 1964, **17**, 544.

[30] R. E. Gilbert and K. Lonsdale, *Acta Cryst.*, 1956, **9**, 697.

[31] N. Sklar, M. E. Senko, and B. Post, *Acta Cryst.*, 1961, **14**, 716.

[32] C. Romer and J. E. G. Creutzberg, *Rec. Trav. chim.*, 1956, **75**, 331.

[33] J. D. Lee and S. C. Wallwork, *Acta Cryst.*, 1959, **12**, 210.

[34] O. Hassel and K. O. Strømme, *Acta Chem. Scand.*, 1959, **13**, 275.

[35] For hydrogen bonding with urea see S. V. Deshapande, C. C. Meredith, and R. A. Pasternak, *Acta Cryst.*, 1968, **B24**, 1396, and ref. 27; for hydrogen bonding to acetone see refs. 31 and 32.

[36] W. C. Hamilton and J. A. Ibers, 'Hydrogen Bonding in Solids,' Benjamin, New York, 1968.

[37] P. Coppens, T. M. Sabine, R. G. Delaphane, and J. A. Ibers, *Acta Cryst.*, 1969, **B25**, 2451.

[38] J. C. Taylor and T. M. Sabine, *Acta Cryst.*, 1972, **B28**, 3340.

[39] P. Coppens and A. Vos, *Acta Cryst.*, 1971, **B27**, 146. G. C. Verschoor and E. Keulen, *ibid.*, p. 134.

[40] J. Almlöf, Å. Kvick, and J. O. Thomas, *Acta Cryst.*, in the press (Abstracts First European Cryst. Conf., Bordeaux, Group B3, 1973).

bution of the Coulombic interactions to E_{nb} is $<20\%$. They are also not significantly dependent on the angle of rotation, in contrast to the other terms in equation (1), for which the repulsive interactions exert a dominant effect with increasing angle of rotation. As a consequence, the conformational preference is the same whether or not the Coulombic forces are included (Table 3).

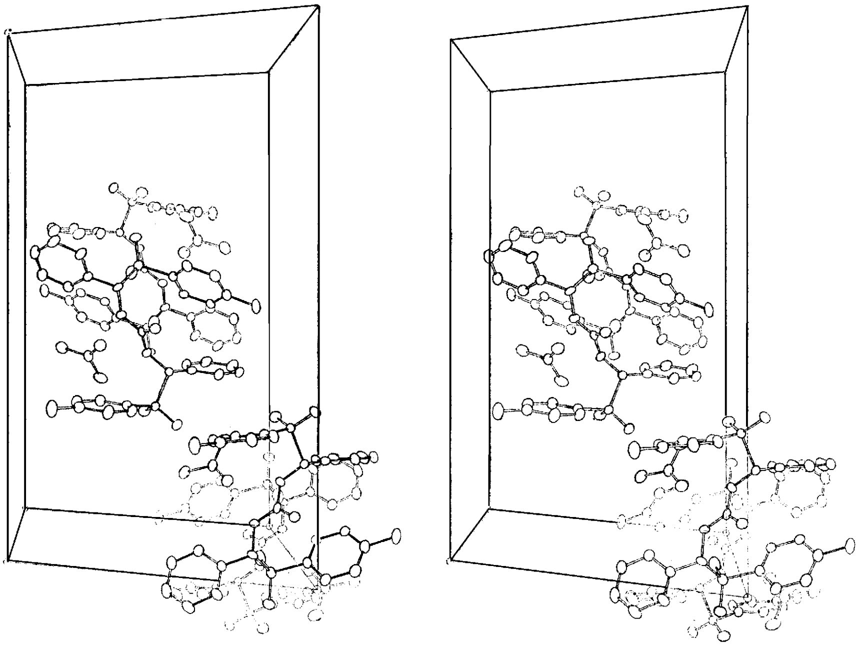


FIGURE 2 Stereoscopic projection of the unit cell contents on (001)

In the corresponding calculations on the isolated molecule, differences in the relative contributions of the Coulombic interactions are also of minor importance. If the energy is at a minimum, the relative contributions of the attractive and repulsive interactions are nearly equal. This contrasts with the results of calculations for the crystal, where the attractive interactions in the same conformation are found to be $>50\%$ of the total energy.

TABLE 3

Rotation(°) by which E_{nb} is a minimum [a] for (*A*) (1) as acetone solvate, and (*B*) omitting acetone from the calculation

Rotation axis [b]	(*A*)	(*B*)
N(01)–C(08)	0 (0) [c]	0 (0)
C(08)–C(09)	−4 [d] (−4)	−4 (−4)
C(08)–S(01)	0 (0)	−2 (−2)
N(02)–C(16)	−4 (−4)	−4 (−4)
C(16)–C(17)	−6 (−6)	−6 (−5)
C(16)–S(02)	0 (1)	−2 (−2)

[a] Co-ordinates from crystal structure. During rotation around a particular bond, no change in the configuration around any other bond was introduced. [b] See Figure 1 for atom numbering. [c] The values in parentheses indicate rotations obtained when net charges on atoms are ignored ($q = 0$) in the calculation of E_{nb}. [d] A minus sign indicates clockwise rotation [*e.g.* viewed in the direction from C(08) to C(09) there is a clockwise rotation of 4°].

Unfortunately, the potential-energy wells corresponding to rotation around the different bonds in the isolated molecule, are much less steep than those for the crystal. Nevertheless, the results clearly indicate a tendency for favouring a conformation similar to that found in the solution. These results may indicate that we have previously overestimated the dominating importance of intramolecular dipolar interactions in determining the folding of the molecule.

Comparison of Data for Solution and Solid-state Conformation.—Figure 1 shows that the tosyl methyl groups are positioned in the shielding regions of the diamagnetic ring currents of the benzyl phenyl rings. Using the crystallographic data in a calculation employing Johnson and Bovey's isoshielding lines,[41,42] we find average upfield shifts of 0.08 and 0.21 p.p.m. for the protons attached to C(01) and C(29), resulting in an average shielding of 0.15 p.p.m. Analogously, upfield shifts of 0.55 and 0.26 p.p.m. (mean 0.41 p.p.m.) were calculated for the methine protons H(08) and H(16), respectively. In dimethyl sulphoxide solution,[1] however, a motionally averaged upfield shift of 0.25 p.p.m. is observed for the tosyl methyl protons and one of 0.26 p.p.m. for the methine protons. A satisfactory explanation for these discrepancies could be that, in order to attain the most efficient packing in the crystal, the tosyl group attached to C(08) is somewhat pushed away from its solution position above (or below) the plane of the phenyl ring C(17)—(22). Hence the distance between the phenyl ring C(09)—(14) and the methyl group attached to C(26) is enlarged and, consequently, the

---

[41] J. W. Emsley, J. Feeney, and L. H. Sutcliffe, 'High-Resolution Nuclear Magnetic Resonance Spectroscopy,' Pergamon, Oxford, 1965, p. 595.

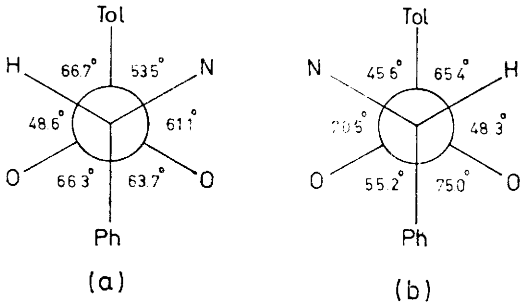
[42] P. J. Rose, *Org. Magn. Resonance*, 1973, **5**, 187.

shielding diminished. At the same time the distances between the methine protons H(08) and H(16) and the phenyl rings C(23)—(28) and C(02)—(07), respectively, become smaller, resulting in an increase of the intramolecular shielding.

In the crystal, the dihedral angles for N(01)-H(101)-C(08)-H(08) and N(02)-H(201)-C(16)-H(16) are 149.3 and 168.7°, respectively. This agrees well with the suggested *trans*-position of the respective protons in the favoured solution conformation as based on the magnitude of the vicinal NHCH coupling constant (*J* 11 Hz).[1]

The position of the tosyl rings with respect to the nearest benzyl moieties is *trans* in the crystal. The same conformation was suggested for the molecule in solution. However, the proclivity to acquire most efficient packing in the crystal may be invoked to explain that the configurations around the S-C(aliphatic) bonds as shown in Figure 3 are not quite the same. The molecule in the crystal has therefore no symmetry, whereas in the solution conformation a C_2 axis is possible.

It may be concluded that the solid-state and the favoured solution conformations of (1) are very similar and that the minor differences arise predominantly from packing in the solid phase, which will, of course, be influenced by the position of the acetone of crystallization. The folding tendency of the molecule is believed to be the result of intramolecular interactions involving mainly repulsive non-bonded interactions.



(a) (b)

FIGURE 3 Configurations around the S-C (aliphatic) bonds, (a) around the S(01)-C(08), and (b) around the S(02)-C(16) bond

We thank Professor Aafje Vos for her interest, Dr. C. T. Kiers for help with the *X*-ray crystallography, and Dr. P. A. Kroon for the program WMIN and for stimulating discussions.

[5/1108 *Received June 6th*, 1975]