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Direct Determination of the Structure of L-Cystine Dihydrobromide

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The structure of L-cystine dihydrobromide has been determined by a statistical method and refined by means of two-dimensional difference syntheses. The unit cell is orthorhombic with

$$a = 17{\cdot}85,\ b = 5{\cdot}35,\ c = 7{\cdot}48\ \text{Å},$$

space group $P2_122_1$. The precision of the structure has been evaluated, and the general features compared with those of other structures containing the cystinyl group.

Aqueous acid solutions of cystine have an unusually high specific rotatory power (Toennies, Lavine & Bennett, 1936). The configuration of the cystinyl group in solids may give information bearing on this anomalous behavior. Furthermore, the possible configurations of this group under varying conditions will be helpful in protein model building. For these reasons we have determined the crystal structure of L-cystine dihydrobromide.

Experimental

Crystals of L-cystine dihydrobromide,

$$\begin{array}{l}\mathrm{S.CH_2.CH(NH_2.HBr)COOH}\\ |\\ \mathrm{S.CH_2.CH(NH_2.HBr)COOH}\,,\end{array}$$

satisfactory for collecting X-ray diffraction data were grown from an aqueous HBr solution of L-cystine by slow evaporation of the solvent at room temperature. The crystals frequently grow as needles elongated along b, outlined by $\{101\}$ and $\{100\}$ and terminated by $\{110\}$ and $\{010\}$.

Unit-cell parameters were determined from Weissenberg and oscillation photographs and found to be:

$$a = 17{\cdot}85,\ b = 5{\cdot}35,\ c = 7{\cdot}48\ \text{Å},$$

based on Cu $K\alpha$ $\lambda = 1{\cdot}5418$ Å. The unconventional orientation to which this choice of axes corresponds was used to preserve simplicity in comparing with L-cystine dihydrochloride (Steinrauf, Peterson & Jensen, 1958).

The only systematic absences of reflections were $h00$ for h odd and $00l$ for l odd. It was assumed, therefore, that the space group is $P2_122_1$. For 2 molecules per unit cell the calculated density is 1·869 g.cm.$^{-3}$; observed by flotation, 1·870 g.cm.$^{-3}$.

Intensities on unidimensionally integrated Weissenberg photographs were measured with a microdensitometer (Jensen, 1954) and recorded with a logarithmic slide wire recorder. Within the linear response range of the film, the area under the recorder tracing is proportional to the integrated intensity.

The crystals are elongated along b and are of sufficiently uniform cross section as obtained from solution so that specimens may be chosen which yield satisfactory $h0l$ data. To obtain good $hk0$ data, however, it was necessary to cut the needles. This was done by cutting a rough section with a razor blade and trimming with the solvent saw shown in Fig. 1. Elaborate devices have been described (Maddin & Asher, 1950; McGuire, 1949), but the ease of cutting, the general versatility and the small expenditure of time necessary to set up a simple apparatus are probably not generally appreciated. Only about two hours were required to assemble the necessary pieces of apparatus, and about half an hour was sufficient to cut a good cylinder 0·2 mm. in diameter. Because of the relative hardness, grinding would probably have worked equally well for crystals of L-cystine dihydrobromide, but for soft crystals such as many paraffin chain compounds grinding fails completely while the solvent saw works well.

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Initially some difficulty may be experienced in using the simple form of the apparatus shown in Fig. 1. However, if the solvent and the distance of the crystal from the solvent are varied, it is quite easy simply by moving the Erlenmeyer flask to regulate the position of the string so that cutting and trimming operations proceed smoothly.

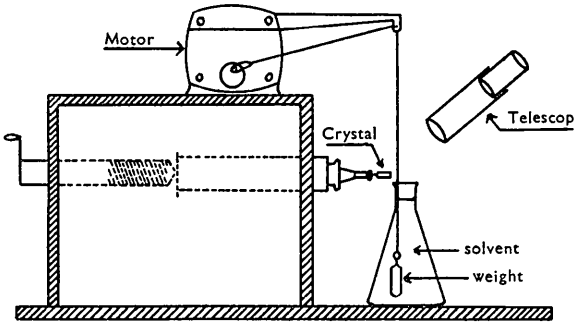


Fig. 1. Solvent saw.

A useful modification of this device may be made by adding a motor to rotate the crystal. It is convenient to mount the crystal in the usual goniometer head so that it may be aligned by appropriate X-ray means before being cut in such a lathe.

Determination of the structure

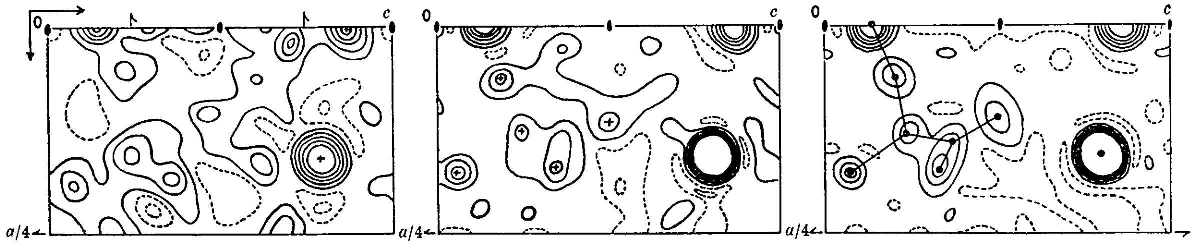
The $h0l$ intensities were scaled in the usual way (Wilson, 1942) although this was unnecessary for the subsequent solution of the structure.

It was decided to attempt a direct solution of the structure projected on (010) by the statistical method based on Sayre's equation (Sayre, 1952; Zachariasen, 1952). Although this structure does not have equal atoms, a fundamental assumption in Sayre's derivation, we may look at it from the standpoint of the single heaviest atom per asymmetric unit as constituting a simple 3 parameter problem. It is legitimate to consider the C, N and O atoms as negligible, but the S atom with almost half as many electrons as Br^- would be expected to perturb the statistics.

A solution was attempted by writing down the 30 most intense reflections, and the signs of two appropriate ones were chosen arbitrarily. From these, signs were determined as $+$, $-$ or $\pm a$ where a may be $+$ or $-$. No relation was found among these most intense reflections by which a might be determined. From the space group, it is clear that in projection on (010) no two atoms can lie within an atomic radius of the points $0,0$; $0,\frac{1}{2}$; $\frac{1}{2},0$; $\frac{1}{2},\frac{1}{2}$. This offered a possible rapid and simple means of choosing the appropriate sign of a. The 30 F's for the two possible values of a were added together with the appropriate alteration of sign for each of the above four points. One of the signs for a gave dramatically better results than the other, i.e. low electron density at all four points. Only one of the 28 directly determined signs subsequently proved to be wrong. Fig. 2(a) shows an F_o synthesis based on the 30 most intense reflections.

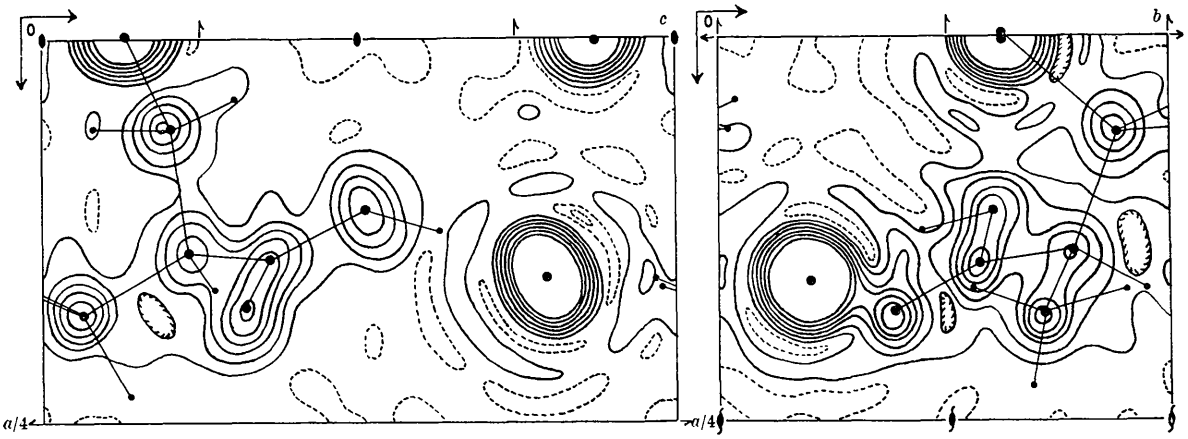
A set of structure factors was calculated assuming the highest peak to be Br^- and the next highest to be the S atom (indicated by + in Fig. 2(a)). Interpolated values were used for f_S (Steinrauf, Peterson & Jensen, 1958), and for convenience in calculating on the I.B.M. type 604 electronic computer f_{Br^-} was taken as equal to $2f_{Cl^-}$. This resulted in a reliability index $R = 37{\cdot}9\%$. Fig. 2(b) shows the F_o synthesis based on the signs of the first F_c. The electron density in the two heavier atoms and the electron distribution over the rest of the map is much improved. Another set of structure factors was then calculated on the basis of the Br^-, the S atom and five light atoms assumed to be N atoms (indicated by + in Fig. 2(b)). R decreased to $25{\cdot}7\%$. Fig. 2(c) shows the third F_o synthesis based on the signs of these F_c. At this stage the molecule is obvious, and it is no longer possible to avoid assigning C, N and O atoms, Fig. 4(a), (b)).

Three additional cycles of refinement using ΔF syntheses (Cochran, 1951) reduced R to $13{\cdot}3\%$. It was clear at this point that assuming the electron density of Br^- equal to $2\,Cl^-$ was sufficiently in error so as to impede the progress of the refinement. From this point on, structure factors were calculated using *Internationale Tabellen* (1935) values for Br atom without dispersion, interpolated values for the S atom



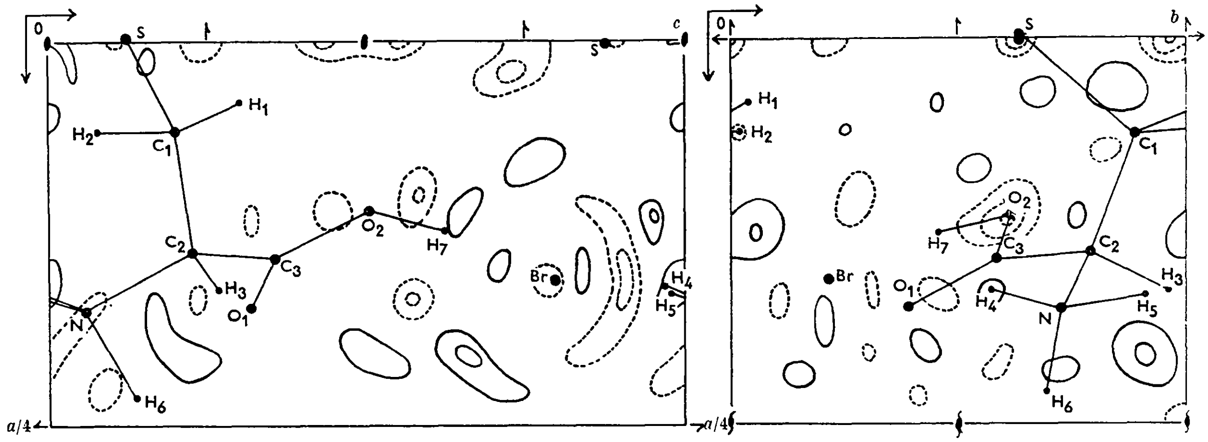
(a) (b) (c)

Fig. 2. Initial F_o syntheses. Positive contours solid, zero and negative broken. Contour interval 3 e.Å^{-2}. Contours for electron densities exceeding 15 e.Å^{-2} omitted. (a) Syntheses using 30 most intense F_o and signs determined statistically. (b) Synthesis using all F_o and signs determined by Br^- and S atom. (c) Synthesis using all F_o and signs determined by Br^-, S atom and 5 lighter atoms assumed to be nitrogen.



(a) (b)

Fig. 3. Final F_o syntheses. Positive contours solid, zero and negative broken. Contour interval 2 e.Å^{-2}. Contours for electron density exceeding 12 e.Å^{-2} omitted.



(a) (b)

Fig. 4. Final ΔF syntheses. Positive contours solid, negative broken and zero contour omitted. Contour interval, 0·5 e.Å^{-2}

and McWeeny values for the H, C, N and O atoms (McWeeny, 1951). Final $R_{h0l} = 7{\cdot}1\%$ if unobserved and three seriously extinguished reflections are neglected.

Relative y coordinates were assigned from approximate expected bond lengths and the x coordinates from the projection on (010). The approximate position of the molecule was determined from packing considerations and a few low index weak or intense reflections. Refinement proceeded through F_o and ΔF syntheses. Final $R_{hk0} = 7{\cdot}1\%$ if unobserved and eight extinguished reflections are neglected. Final F_o and ΔF maps are shown in Figs. 3 and 4.

Hydrogen atom coordinates were chosen on the basis of a model fitted to the H atom peaks of the appropriate ΔF synthesis. Peaks appeared for all H atoms although their height and position are much poorer than for a structure containing only C, N and O atoms in addition to H atoms. It is worth noting, however, that without taking special precautions in collecting the intensity data, the H atoms did show even though well over half the electrons are associated with the Br^- and S atom.

Of the 283 reflections for the two zones, nine were sufficiently extinguished to be ignored and 42 were unobserved. From the remaining 232, 24 positional, 14 temperature factor and two scale parameters were determined. Thus there are 5·8 observations per parameter.

Observed structure factors and final F_c are listed in Table 1. F_{h0l} have been calculated from the coordinates of Table 2 which are referred to an origin on $\bar{1}2\bar{1}$ in the plane of 2_12_1. For convenience F_{hk0} have been calculated using as origin $x = -\frac{1}{4}$, $y = 0$. Bond lengths and angles appear in Table 3.

Individual atom anisotropic temperature factor parameters were determined for the Br^- and S atom from the later ΔF syntheses and appear in Table 4.

Table 1. *Observed and calculated structure factors*

hkl	F_o	F_c
200	21·7	21·7
400	67·2	−102·8
600	98·1	−185·6
800	11·8	16·6
10,0,0	43·4	44·8
12,0,0	72·6	80·7
14,0,0	32·8	−31·8
16,0,0	14·5	− 9·3
18,0,0	37·1	−39·8
20,0,0	31·0	31·1
22,0,0	< 3·4	4·6
010	40·8	−46·3
110	24·2	22·3
210	22·2	19·0
310	72·6	−109·8
410	24·2	−21·0
510	7·8	− 9·7
610	25·3	26·2
710	28·7	28·7
810	34·3	−38·3
910	71·2	89·6
10,1,0	49·8	52·2
11,1,0	16·0	−16·3
12,1,0	13·6	− 8·9
13,1,0	32·9	−31·8
14,1,0	7·3	3·0
15,1,0	49·4	−52·2
16,1,0	25·7	−25·8
17,1,0	29·5	31·2
18,1,0	< 5·5	6·7
19,1,0	18·8	20·1
20,1,0	7·5	− 4·9
21,1,0	22·1	23·5
22,1,0	16·7	16·8
020	71·0	−90·9
120	57·4	−69·5
220	45·6	−46·3
320	13·9	−14·8
420	49·9	51·5
520	25·4	−26·4
620	70·5	77·1
720	71·2	81·4
820	12·2	11·4
920	19·2	−20·9
10,2,0	46·6	−44·2
11,2,0	18·0	18·4
12,2,0	39·3	−39·3
13,2,0	51·1	−46·9
14,2,0	< 5·7	5·3
15,2,0	< 5·8	1·1
16,2,0	27·0	27·6
17,2,0	< 5·5	− 3·2
18,2,0	16·4	13·5
19,2,0	31·9	32·5
20,2,0	6·0	− 7·4
21,2,0	8·3	− 9·3
030	30·6	−26·1
130	53·1	56·1
230	33·6	−34·0
330	14·4	14·3
430	55·8	58·0
530	10·0	8·4
630	20·8	20·8
730	48·3	−50·2
830	15·2	14·0
930	13·4	− 7·7
10,3,0	61·1	−62·7
11,3,0	7·3	− 2·9
12,3,0	8·5	− 6·8
13,3,0	45·3	43·3
14,3,0	8·1	8·7
15,3,0	5·7	2·9
16,3,0	38·0	37·3
17,3,0	< 5·0	2·3
18,3,0	4·5	− 2·9
19,3,0	32·9	−34·1
20,3,0	7·4	− 6·1
040	11·8	−13·4
140	23·1	22·6
240	35·9	36·6
340	45·4	43·6
440	32·3	−30·7
540	21·9	20·4
640	5·6	− 4·6
740	19·6	−23·6
840	20·9	−21·2
940	37·1	−37·8
10,4,0	32·0	31·3
11,4,0	< 5·7	− 6·9
12,4,0	< 5·6	− 0·7
13,4,0	23·8	24·9
14,4,0	13·6	13·8
15,4,0	18·6	21·0
16,4,0	25·4	26·0
17,4,0	4·5	2·4
18,4,0	7·4	8·6
050	58·4	58·9
150	12·8	12·7
250	9·8	7·5
350	18·4	16·0
450	28·5	25·6
550	10·6	9·0
650	51·3	48·8
750	7·7	6·8
850	16·0	18·7
950	7·8	7·7
10,5,0	20·1	19·0
11,5,0	9·1	10·1
12,5,0	27·9	26·2
13,5,0	8·6	9·5
14,5,0	15·1	−16·6
15,5,0	3·2	3·3
060	5·1	− 4·8
160	9·3	− 6·6
260	< 4·8	− 1·0
360	41·1	−38·9
460	< 4·6	1·6
560	< 4·5	− 2·2
660	< 4·3	0·7
760	< 4·1	3·1
860	< 3·8	2·6
960	38·0	38·2
10,6,0	< 3·1	1·6
11,6,0	< 2·9	− 5·3
101	43·9	43·6
201	34·3	33·0
301	16·0	12·7
401	49·5	−50·0
501	67·2	71·6
601	39·6	−36·1
701	36·2	32·5
801	59·3	62·9
901	21·1	−21·3
10,0,1	15·7	−13·0
11,0,1	32·7	26·1
12,0,1	25·4	−21·1
13,0,1	37·4	38·5
14,0,1	61·5	60·2
15,0,1	< 6·2	5·4
16,0,1	< 6·3	− 1·9
17,0,1	17·0	13·0
18,0,1	26·6	−26·9
19,0,1	17·9	17·2
20,0,1	31·8	33·0
21,0,1	< 4·5	5·5
22,0,1	< 3·7	4·4
002	90·9	−109·8
102	59·6	63·0
202	29·0	26·4
302	6·4	5·1
402	43·7	45·3
502	67·5	−70·5
602	81·0	−85·2
702	46·0	45·0
802	13·2	11·4
902	33·8	31·3
10,0,2	65·5	68·6
11,0,2	34·3	−31·8
12,0,2	41·2	−40·7
13,0,2	24·1	21·7
14,0,2	29·6	−29·3
15,0,2	31·6	32·1
16,0,2	29·3	30·0
17,0,2	13·2	−13·7
18,0,2	13·0	−11·0
19,0,2	< 5·5	3·8
20,0,2	17·2	−18·3
21,0,2	17·5	20·1
22,0,2	13·9	14·4
103	75·5	−79·5
203	46·5	−45·0
303	16·9	14·4
403	54·6	56·8
503	13·5	−12·8
603	14·0	12·5
703	63·3	−64·7
803	42·6	−42·6
903	7·6	3·8
10,0,3	30·5	26·5
11,0,3	9·9	− 9·4
12,0,3	17·4	16·6
13,0,3	53·3	−51·8
14,0,3	28·7	−28·0
15,0,3	< 5·1	4·3
16,0,3	9·3	8·1
17,0,3	6·1	− 8·7
18,0,3	18·3	20·2
19,0,3	36·5	−40·2
20,0,3	4·4	− 7·2
21,0,3	< 3·6	2·3
004	14·0	10·7
104	82·5	−87·0
204	36·2	−33·1
304	4·7	− 2·6
404	62·9	−61·9
504	81·6	84·8
604	17·4	−15·0
704	58·6	−57·4
804	17·8	−16·8
904	21·2	−17·8
10,0,4	41·0	−39·2
11,0,4	44·9	42·8
12,0,4	15·9	−16·4
13,0,4	32·1	−32·7
14,0,4	12·1	−12·6
15,0,4	23·9	−21·7
16,0,4	26·2	−25·1
17,0,4	23·2	25·1
18,0,4	8·7	− 8·8
19,0,4	< 4·4	− 5·2
20,0,4	< 3·6	− 5·7
105	24·1	22·3
205	< 5·4	3·4
305	63·7	−64·0
405	< 5·5	− 3·6
505	6·9	− 0·3
605	10·9	−10·5
705	36·9	32·9
805	< 6·1	− 1·8
905	61·2	−60·6
10,0,5	< 6·3	0·3
11,0,5	26·4	−25·1
12,0,5	11·4	−11·6
13,0,5	36·8	38·1
14,0,5	< 6·0	− 2·4
15,0,5	21·8	−22·7
16,0,5	< 5·3	− 0·6
17,0,5	20·1	−22·1
18,0,5	11·9	−13·2
19,0,5	17·6	19·8
006	38·1	28·4
106	34·0	32·4
206	< 6·1	1·8
306	< 6·1	− 2·0
406	< 6·2	− 3·5
506	45·2	−45·2
606	22·1	17·5
706	23·6	22·2
806	< 6·3	3·1
906	13·1	14·0
10,0,6	< 6·2	1·8
11,0,6	33·6	−35·2
12,0,6	18·7	14·8
13,0,6	12·2	12·1
14,0,6	< 5·3	− 0·6
15,0,6	14·5	18·0
16,0,6	< 4·2	− 2·6
17,0,6	24·1	−27·9
107	20·7	−19·5
207	22·6	20·8
307	64·1	64·4
407	16·1	−15·4
507	12·5	10·4
607	16·0	−12·5
707	15·4	−17·2
807	19·7	19·5
907	39·8	44·4
10,0,7	< 5·5	− 4·8
11,0,7	17·7	20·2
12,0,7	9·7	−10·1
13,0,7	10·1	−12·8
14,0,7	11·8	15·1
15,0,7	16·2	18·3
008	16·8	−16·9
108	12·5	−12·6
208	26·0	24·5
308	< 5·6	− 0·4
408	20·8	21·8
508	17·9	19·7
608	16·6	−15·0
708	< 5·1	− 4·9
808	26·1	27·1
908	5·7	− 6·8
10,0,8	23·6	24·3
11,0,8	11·1	14·2
12,0,8	10·6	−12·0
109	7·0	10·2
209	20·7	−22·7
309	5·9	− 7·7
409	21·1	22·4
509	< 3·8	1·5
609	12·7	14·0
709	9·6	12·5

Table 2. *Atomic coordinates*

Atom	x/a	y/b	z/c
C_1	0·0606	0·8820	0·2050
C_2	0·1394	0·7905	0·2320
C_3	0·1457	0·5745	0·3608
N	0·1795	0·7210	0·0641
O_1	0·1795	0·3845	0·3233
O_2	0·1128	0·6097	0·5091
S	0·9963	0·6254	0·1350
Br^-	0·1579	0·2046	0·7984
H_1	0·059	0·010	0·080
H_2	0·042	0·040	0·307
H_3	0·165	0·950	0·277
H_4	0·162	0·560	0·973
H_5	0·165	0·900	0·980
H_6	0·232	0·680	0·145
H_7	0·125	0·450	0·625

Table 3. *Bond lengths and angles*

S–S′	2·024 Å	S′–S–C_1	103·9°
S–C_1	1·862	S–C_1–C_2	111·9
C_1–C_2	1·506	C_1–C_2–C_3	113·9
C_2–C_3	1·509	C_1–C_2–N	114·7
C_2–N	1·493	C_2–C_3–O_1	122·0
C_3–O_1	1·215	C_2–C_3–O_2	114·2
C_3–O_2	1·269	N–C_2–C_3	108·1
Br^-–H_7–O_2	3·17	O_1–C_3–O_2	123·8
Br^-–H_5–N′	3·28		
Br^-–H_4–N″	3·42		
Br^-–H_6–N‴	3·41		

Table 4. *Temperature factor parameters*
$\exp-[(A+C\cos^2\varphi)\sin^2\theta/\lambda^2]$*

	A_{hk0} (Å^2)	C_{hk0} (Å^2)	ψ_{hk0} (°)†	A_{h0l} (Å^2)	C_{h0l} (Å^2)	ψ_{h0l} (°)†
C_1	1·70	0·00	—	1·70	0·00	—
C_2	1·70	0·00	—	1·70	0·00	—
C_3	1·70	0·00	—	1·70	0·00	—
N	1·70	0·00	—	1·70	0·00	—
O_1	3·50	0·00	—	3·50	0·00	—
O_2	3·50	0·00	—	3·50	0·00	—
Br^-	2·04	0·80	−40·0	1·65	1·10	−54·0
S	1·19	1·41	0·0	1·10	1·40	14·4

* φ is the angle between the normal to a plane and the direction of maximum vibration.

† ψ_{hk0} and ψ_{h0l} are angles between directions of maximum vibration and b^* and c^* respectively.

Machine calculations

This structure was solved when the only electronic computing equipment available to us was an I.B.M. type 604 computer. Since then an I.B.M. type 650 has become available. L-cystine dihydrobromide was used as a test case in checking out some of the programs for the type 650 and final calculations for this structure were done on that machine.

For the programs written in these laboratories, the type 650 is 20–30 times as fast as the type 604 when computing structur factors and Fourier syntheses. Structure factors for the 170 $h0l$ reflections can be calculated in about 8·5 minutes when individual atom anisotropic temperature factors are included. Either F_o or ΔF syntheses on (010) calculated on a grid $a/100$ and $c/25$ over the unique area of the unit cell requires about 9·5 minutes. This time includes program load, punch out and listing of the final map in a form suitable for drawing contours.

Accuracy of results

Standard deviations in the coordinates were calculated from the ΔF's by Cruickshank's method (Cruickshank, 1949). For L-cystine dihydrobromide, $\sigma(A_h)=-1{\cdot}616$, $\sigma(A_k)=-1{\cdot}495$, $\sigma(A_l)=-1{\cdot}627$. From the r.m.s. value, 1·580, and an average curvature, standard deviations in the coordinates for each atom type have been calculated and are listed in Table 5 along with the ϱ_0 values used in computing the curvatures.

Table 5. *Standard deviations in coordinates and peak density ϱ_0 for each atom type*

Atom type	$\sigma_{\text{coordinate}}$	ϱ_0
C	0·021 Å	8·5 e.Å^{-2}
N	0·018	10
O	0·017	11
S	0·0048	29
Br^-	0·0018	70

The electron density for a number of atoms is closely approximated by the equation (Costain, 1941; Booth, 1946):

$$\varrho_r=\varrho_0\exp(-pr^2)\ .$$

The same equation represents closely the projected electron density and leads to the following relation:

$$(d^2\varrho/dr^2)_{r=0}=-2\pi\varrho_0^2/n\ ,$$

where $(d^2\varrho/dr^2)_{r=0}$ is the central curvature and ϱ_0 the peak density of the projected electron density and n is the number of electrons associated with the atom. The ϱ_0 values of Table 5 were obtained from peak heights of the F_o syntheses with reasonable adjustment depending on the peak position with respect to the diffraction maxima and minima of the heavy atoms.

The ϱ_0 values will not in general be the same for all atoms of a given type nor for the same atom when projected in different directions. Furthermore, for a given atom in a given projection, the curvature will vary with direction. In the present work, 'average' curvatures are regarded as sufficiently accurate.

No correction has been made for absorption of X-rays in the crystals nor for dispersion by Br^-. Partial allowance for secondary extinction has been made by coding the most intense reflections so that they were omitted from ΔF syntheses and included as F_c in F_o syntheses. It is clear from approximate values for the secondary extinction coefficients for the two crystals used that a correction should be applied to all intense reflections and preferably to the whole set of data.

The decrease in the precision of the light atom positions, due to the presence of heavy atoms, is evident by comparing the results from the present structure with those from *n*-dodecanoic acid hydrazide (Jensen, 1956). Both structures were based on data from two zones collected in the same way and refined to comparable values of R. But σ_c for this structure exceeds σ_c for *n*-dodecanoic acid hydrazide by a factor of about 2·5.

Discussion

Although L-cystine dihydrobromide crystallizes in a crystal system and space group different from that for L-cystine dihydrochloride, nevertheless the general features of the structures are similar. In both, the molecule has a two-fold axis, the configuration of the cystinyl group is the same and the unit-cell dimensions are not very different.

The distance per cystinyl group along a^* in L-cystine dihydrobromide is 4·46 Å compared with 4·52 Å in the dihydrochloride. These distances are close to the corresponding spacing (along the c^* axis) of 4·69 Å in hexagonal L-cystine. Indeed, except for the contribution of the halide ions in the salts, F_{h00} are relatively the same as F_{00l} for hexagonal L-cystine. Thus except for the electron density of the halide ions, $\varrho(x)$ for the salts is approximately equal to $\varrho(x)$ for the hexagonal phase of the free acid. Comparison with the published structure verifies this conclusion (Oughton & Harrison, 1957).

Table 6. *Standard deviations in bond lengths*

Bond	Length
C–C	0·030 Å
C–N	0·027
C–O	0·027
C–S	0·021
S–S	0·014

Standard deviations of the more important bond lengths appear in Table 6. They indicate that within the cystinyl group there is no significant difference from expected values nor from values for corresponding bonds in L-cystine dihydrochloride. The O–H–Cl^- and the three N–H–Cl^- bonds in L-cystine dihydrochloride range from 2·98–3·27 Å. The corresponding bonds in L-cystine dihydrobromide range from 3·17–3·42 Å. The hydrogen bonds to Br^- average 0·175 Å longer than those to Cl^-. This difference is essentially the same as the difference in the ionic radii of Cl^- and Br^-, 0·2 Å (Pauling, 1939).

Table 7. *Intermolecular distances*

Atom	Nearest neighbor
C_1	O_1, 3·54 Å
C_2	O_1, 3·33
C_3	Br^-, 3·73
N	O_1, 3·15
O_1	N, 3·15
O_2	Br^-, 3·17*
S	O_2, 3·30
Br^-	O_2, 3·17*

* O–H–Br^- hydrogen bond.

The smallest intermolecular distance for each atom in the asymmetric unit other than hydrogen has been calculated, Table 7. There are no abnormally small intermolecular distances.

One of the objects of this work was to obtain from the solid state structural information that might bear on the anomalously large values for the optical rotatory power of aqueous acid solutions of cystine. Comparison of the optical rotatory power of cystine and cysteine in 1 N HCl indicates that the anomalous value for cystine is to be attributed primarily to the disulfide group. In L-cystine dihydrobromide, L-cystine dihydrochloride and N,N′-diglycyl-L-cystine dihydrate, (Yakel & Hughes, 1954) the configuration of the molecule is the same. In hexagonal L-cystine a different, but related, configuration is found. Regardless of the configuration, however, the C′–S′–S–C dihedral angle is essentially the same for each compound and roughly equal to 90°. In the solid state, therefore, this configuration represents relatively low energy. Probably in solution also, this will represent a configuration approximated by an appreciable number of the molecules at any instant. It is tempting to postulate that this particular feature of the structure gives rise to the anomalous values of the optical rotatory power of the acid solutions of L-cystine.

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