Acta Cryst. (1974). B**30**, 711

The Crystal and Molecular Structure of Tetragonal L-Cystine

BY MICHAEL O. CHANEY* AND LARRY K. STEINRAUF

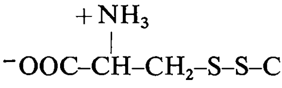
Department of Biochemistry, Indiana University School of Medicine, Indianapolis, Indiana 46202, *U.S.A.*

(*Received* 8 *October* 1973; *accepted* 27 *November* 1973)

The crystal structure of tetragonal L-cystine has been determined from three-dimensional X-ray data. The space group is $P4_1$, with $a=6{\cdot}710$ (5) and $c=21{\cdot}73$ (1) Å; $Z=4$. The structure was solved by a combination of the E^2-1 Patterson function to locate the two S atoms, block-diagonal least-squares refinement of the S coordinates, and tangent-formula phase refinement. The final structure refinement used the full-matrix least-squares method with anisotropic temperature factors for S, O, and N and isotropic terms for C and H. Difficulty was encountered during the final refinement since the molecule contained a pseudo-twofold axis of symmetry. The final R index was 0·097, based on 962 independent non-zero reflections. The disulfide dihedral angle was found to be 69·3°. The molecular conformation is observed to be similar to that of hexagonal L-cystine, with a right-handed disulfide chirality.

Introduction

Cystine (I) structure determinations have been undertaken in this laboratory mainly to determine the range of possible crystal conformations and correlate them with disulfide chirality.



$$^{-}OOC\text{-}\overset{\overset{+NH_3}{|}}{C}H\text{-}CH_2\text{-}S\text{-}S\text{-}CH_2\text{-}\overset{\overset{+NH_3}{|}}{C}H\text{-}COO^{-}$$

(I)

Previous structure determinations of L-cystine compounds have shown that N,N'-diglycyl-L-cystine (Yakel & Hughes, 1954), L-cystine dihydrochloride (Steinrauf, Peterson & Jensen, 1958), L-cystine dihydrobromide (Peterson, Steinrauf & Jensen, 1960), and L-cystine diamide dihydrochloride (Chaney & Steinrauf, 1968) all possess a left-handed disulfide chirality and similar molecular conformation. Hexagonal L-cystine (Oughton & Harrison, 1959) and now tetragonal L-cystine in this work possess a right-handed disulfide chirality and a molecular conformation which is different from the above class of cystine compounds. The definition of disulfide chirality is illustrated in Fig. 1.

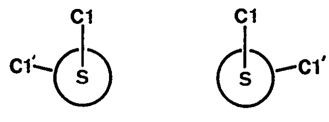


Fig. 1. Illustration of right-handed and left-handed disulfide chirality by use of Newman projections. The projections are down the S–S′ bond.

Experimental

Preparation

L-Cystine was dissolved in a warm 6N ammonium hydroxide solution and crystallized by evaporation at room temperature. Both plates of the hexagonal form and prisms of the tetragonal form were obtained, the former being by far the more numerous.

Crystal data

$C_6H_{12}N_2O_4S_2$	F.W. 240·3
$a=$ 6·710 (5) Å	μ(Mo $K\alpha$) = 5·24 cm^{-1}
$c=$ 21·73 (1)	Crystal size: 0·02 × 0·02 × 0·016 cm
$D_{calc}=$ 1·642 g cm^{-3}	$Z=4$
$D_{obs}=$ 1·622	Space group: $P4_1$.

The unit-cell dimensions and estimated standard deviations were obtained from Weissenberg photographs, with calibration lines from aluminum ($a_0=4{\cdot}0489$ Å at 20°C) superimposed. Precession and Weissenberg photographs of a tetragonal crystal showed systematic $00l$ extinctions for $l=4n+1,2,3$. Because these photographs exhibited possible mirror symmetry, it was difficult to determine the Laue group ($4/m$ or $4/mmm$). Also, the $h00$ reflections for $h=2n+1$ were either absent or very weak. As a result, the space group assignment was ambiguous and was limited to $P4_1$, $P4_12_12$, and $P4_122$. The enantiomorphs to the above space groups were unlikely candidates, since it is known that molecules of L-cystine pack in a left-handed sense about a screw axis.

Intensity data

Intensity data were collected with Zr-filtered Mo $K\alpha$ ($\lambda=0{\cdot}71069$ Å) radiation by the sixth-scan method (Pinkerton & Steinrauf, 1967) on a Supper–Pace autodiffractometer about the b^* axis ($k=0$–7) out to a minimum spacing of 0·8 Å. 2226 reflections ($\pm h,k,l$) were

---

* The Lilly Research Laboratories, Eli Lilly and Company, Indianapolis, Indiana 46206, U.S.A.

measured, 2104 of which were observed greater than zero. This set of data was twofold redundant for space group $P4_1$ and fourfold redundant for the space groups with $4/mmm$ Laue symmetry. The equivalent data sets ($F_{hkl} \equiv F_{\bar{k}hl}$) were used to scale between levels, and the twofold redundant data were used to solve the structure. Because of the low absorption coefficient (5·24 cm^{-1}) and the small size of the crystal, absorption corrections were neglected. Both structure factors and normalized structure factors $|E|$ were calculated after corrections for Lorentz and polarization effects had been applied. The atomic scattering factor curves were taken from *International Tables for X-ray Crystallography* (1962).

An examination of the Patterson map revealed a peak approximately 2 Å from the origin along the c axis, which suggested that the disulfide bond may be in this direction. The same conclusions were reached from efforts to pack four L-cystine molecules from hexagonal L-cystine (Oughton & Harrison, 1959) into the tetragonal unit cell. When the molecules were oriented with their disulfide bonds parallel to **c** and in either the (110), ($\bar{1}$10), ($\bar{1}\bar{1}$0), or (1$\bar{1}$0) planes, a set of molecular dimensions calculated from the tetragonal cell parameters was in excellent agreement with that of hexagonal L-cystine (Table 1).

After the disulfide orientation was known, the Harker sections were interpreted, and the positions for the two non-equivalent sulfurs, S(1) and S(2), were determined. These positions were refined by block-diagonal least-squares calculations (unit weights and B = 3·5 Å^2) to an R index of 0·396. The quantity minimized was $\sum w(F_o - F_c)^2$. All initial considerations indicated the structure to be in the lower-symmetry space group $P4_1$. Because the origin along the 4_1 screw axis was not defined by symmetry, the z coordinate of S(1) was held fixed during refinement. The least-squares program used was a much modified version of the Sparks, Trueblood & Okaya program (*World List of Crystallographic Computer Programs*, 1966). Further refinement was continued with the tangent formula. 237 calculated phases ($|E_h| \geq$ 1·5), based on the two sulfur positions, gave an R = 0·183 ($R = \sum ||E_h|_{\text{obs}} - |E_h|_{\text{calc}}| / \sum |E_h|_{\text{obs}}$), after three cycles of tangent refinement. The new phases were used to calculate an E map, from which 10 of the 14 atoms were located. The remaining non-hydrogen atoms were located from a Fourier map, based on the known atom positions. Further block-diagonal least-squares refinement, using unit weights and anisotropic temperature factors for the sulfur, oxygen, and nitrogen atoms, reduced the R index to 0·125. Fourier difference maps indicated that no anisotropic corrections were neces

Table 1. *A comparison of the molecular dimensions for hexagonal and tetragonal* L-*cystine*

	First dimension perpendicular to disulfide (Å)	Second dimension perpendicular to disulfide (Å)	Third dimension parallel to disulfide (Å)
Tetragonal	4·72 $\left(\frac{a+b}{2}\right)$*	4·72 $\left(\frac{a+b}{2}\right)$	5·43 ($c/4$)
Hexagonal	4·69 ($c/12$)	4·70 $\left(\frac{a_1+a_2}{2}\right)$	5·42 (a_1)

* The symbols enclosed in parentheses represent the directions along which the dimensions were calculated.

Table 2. *Final atomic parameters with estimated standard deviations in parentheses*

All values except the isotropic temperature factors (Å^2) are multiplied by 10^4. The anisotropic temperature factors are expressed in the form $\exp[-(B_{11}h^2 + B_{22}k^2 + B_{33}l^2 + 2B_{12}hk + 2B_{13}hl + 2B_{23}kl)]$.

	x	y	z	B_{11} or B_{iso}	B_{22}	B_{33}	B_{12}	B_{13}	B_{23}
S(1)	1427 (5)	5956 (5)	−461*	161 (8)	145 (7)	24 (1)	35 (6)	−6 (2)	−5 (2)
S(2)	1508 (5)	6603 (5)	457 (3)	185 (8)	179 (8)	18 (1)	74 (6)	24 (2)	25 (2)
O(1)	5411 (16)	2951 (13)	331 (4)	262 (25)	167 (20)	10 (2)	82 (18)	5 (5)	−5 (5)
O(2)	6436 (16)	6022 (17)	380 (4)	247 (27)	336 (32)	9 (2)	−123 (23)	−10 (5)	0 (6)
O(3)	−1906 (15)	10269 (16)	−673 (5)	204 (26)	267 (28)	16 (2)	126 (21)	−13 (5)	−13 (6)
O(4)	1338 (16)	10919 (14)	−770 (5)	264 (27)	166 (22)	14 (2)	−79 (19)	22 (6)	4 (5)
N(1)	4952 (16)	2926 (16)	−877 (5)	175 (24)	162 (24)	9 (2)	40 (18)	3 (5)	8 (5)
N(2)	−1766 (16)	9917 (15)	537 (5)	192 (26)	125 (21)	12 (2)	30 (18)	−8 (6)	5 (5)
C(1)	3950 (18)	6417 (18)	−747 (6)	2·47 (19)					
C(2)	5506 (16)	4844 (18)	−579 (6)	2·38 (19)					
C(3)	5834 (17)	4586 (17)	102 (6)	2·28 (18)					
C(4)	1815 (18)	9266 (19)	483 (6)	2·73 (20)					
C(5)	73 (17)	10526 (16)	248 (6)	2·03 (17)					
C(6)	−190 (19)	10536 (18)	−467 (7)	2·82 (21)					

* This parameter was held constant during refinement.

sary for the carbon atoms. Because the $00l$ data suffered severely from what was probably extinction, it was deleted.

Table 3. *Final positional parameters for hydrogen atoms*

Atomic positions are multiplied by 10^3. All hydrogen atoms were assumed to have an isotropic temperature factor $B=3{\cdot}5$ Å^2.

Hydrogen atom	Attached to	x	y	z
H(1)	C(1)	442	779	−58
H(2)	C(1)	386	649	−123
H(3)	C(2)	688	537	−75
H(4)*	N(1)	388	232	−111
H(5)*	N(1)	504	199	−52
H(6)	N(1)	611	271	−116
H(7)	C(4)	307	962	22
H(8)	C(4)	205	966	95
H(9)	C(5)	45	1199	37
H(10)	N(2)	−300	1071	44
H(11)*	N(2)	−191	990	99
H(12)*	N(2)	−224	863	36

* Positioned by known geometry.

The twofold data were reduced to its unique set of 962 non-zero reflections (for $P4_1$), and a weighting scheme was derived. The $|F_o|$'s were divided into zones of 2·5 e and a mean $|\bar{F}_o|$ and $|\Delta\bar{F}|$ were calculated for each zone. A best-fit curve through the mean values was obtained and expressed as $|\Delta F|=1{\cdot}21+0{\cdot}019|F_o|$. Weights w were assigned such that $w=1{\cdot}21/|\Delta F|$. Refinement, using the above weighting scheme, stopped at $R=0{\cdot}102$ (weighted $R=0{\cdot}130$) after six cycles of full-matrix least-squares calculations (Busing, Martin & Levy, 1962).

All except four hydrogen atoms [H(4), H(5), H(11), and H(12)] were easily located from a three-dimensional difference Fourier map. Peaks corresponding to hydrogen atoms were observed to range in height from 0·7 to 0·9 e Å^{-3}. There were no other peaks above 0·4 e Å^{-3}. The remaining hydrogens were positioned about their respective nitrogens, assuming a tetrahedral arrangement and an N–H bond length of 1·0 Å. With the hydrogen-atom parameters not varied ($B=3{\cdot}5$ Å^2)

Table 4. *Final observed and calculated structure factors*

The columns are l, $10|F_o|$, $10|F_c|$, and $10^3\varphi_c$ (cycles).

l	$10\vert F_o\vert$	$10\vert F_c\vert$	$10^3\varphi_c$
0,1,L			
1	140	123	119
2	301	281	13
3	465	428	880
4	116	129	820
5	220	205	13
6	231	212	845
7	162	182	969
8	298	300	82
9	286	307	237
10	344	349	61
11	330	306	863
12	129	88	190
13	220	227	231
14	225	211	938
15	121	99	60
16	97	116	912
17	101	101	150
18	108	98	68
19	118	99	218
20	44	49	762
21	155	159	153
22	125	118	972
23	114	105	974
24	88	94	842
25	53	42	795
0,2,L			
1	796	767	873
2	289	270	57
3	868	825	90
4	420	425	841
5	207	203	227
6	231	224	143
7	127	135	163
8	87	48	75
9	521	520	794
10	315	289	36
11	462	457	58
12	245	256	234
13	229	256	881
14	101	117	54
15	147	136	60
16	204	180	247
17	110	106	41
18	203	196	956
19	127	128	971
20	62	48	868
21	118	122	885
22	58	54	792
23	95	107	47
24	65	59	162
25	111	109	880
0,3,L			
1	141	138	197
2	797	790	996
3	307	306	770
4	287	261	216
5	263	260	71
6	531	514	915
7	65	86	993
8	185	184	150
9	171	148	156
10	524	537	933
11	188	217	784
12	66	63	973
13	235	249	795
14	252	263	179
15	107	95	770
16	121	106	38
17	86	91	242
18	198	185	822
19	76	73	106
20	64	76	82
21	114	112	204
22	153	153	51
23	78	73	159
24	62	28	781
25	88	83	120
0,4,L			
1	190	213	137
2	126	114	16
3	274	257	24
4	138	115	970
5	214	206	985
6	51	56	892
7	166	153	948
8	244	216	966
9	132	148	70
10	73	63	996
11	65	77	790
12	204	207	993
13	232	212	71
14	49	43	905
15	47	52	55
16	121	124	201
17	168	157	169
18	73	76	941
19	116	121	145
20	69	78	873
21	86	80	929
22	35	33	187
23	28	19	814
0,5,L			
2	87	102	83
3	228	246	848
4	117	102	991
5	53	53	219
6	155	168	788
7	52	32	236
9	276	303	26
10	113	104	230
11	85	101	829
12	105	122	932
13	138	138	966
14	94	99	909
15	51	45	883
16	97	109	104
17	65	76	986
18	81	62	819
19	40	28	959
20	43	40	960
21	84	74	991
1,0,L			
0	32	7	0
1,1,L			
0	1066	1085	0
1	544	546	225
2	573	549	14
3	31	46	637
4	209	214	903
5	295	278	182
6	133	125	888
7	505	511	201
8	506	510	814
9	196	203	910
10	345	366	999
11	270	281	242
12	316	316	178
13	213	230	244
14	125	118	45
15	138	140	966
16	94	74	838
17	123	117	959
18	126	125	949
19	88	104	232
20	86	93	16
21	109	96	199
22	104	105	36
23	103	110	799
24	58	42	932
25	45	46	907
1,2,L			
0	411	394	500
1	892	932	42
2	322	250	76
3	365	383	975
4	166	158	73
5	396	418	90
6	277	255	844
7	255	268	902
8	273	277	26
9	363	355	934
10	169	149	936
11	282	317	921
12	216	175	30
13	330	361	18
14	123	134	135
15	157	163	794
16	181	176	925
17	125	120	107
18	74	62	766
19	176	171	28
20	172	185	962
21	107	121	991
22	64	50	881
23	94	112	816
24	118	95	188
25	87	92	9
1,3,L			
0	167	197	0
1	278	273	229
2	300	303	16
3	113	70	124
4	292	286	912
5	105	41	55
6	129	73	36
7	184	207	956
8	277	302	207
9	391	418	86
10	191	220	980
11	207	231	126
12	241	254	974
13	171	179	60
14	105	42	114
15	162	173	928
16	233	239	222
17	128	147	940
18	141	151	927
19	112	98	102
20	153	181	44
21	100	100	5
22	60	30	128
23	66	58	951
24	59	37	245
25	73	65	166
1,4,L			
0	330	371	0
1	291	302	872
2	431	465	954
3	186	109	173
4	367	391	161
5	239	242	72
6	127	135	789
7	151	189	82
8	230	238	866
9	231	245	203
10	216	233	949
11	137	97	115
12	236	258	996
13	175	215	925
14	212	232	867
15	91	67	987
16	117	105	214
17	152	171	4
18	86	83	194
19	94	92	76
20	101	91	846
21	78	89	812
22	79	91	930
23	53	42	70
1,5,L			
0	242	278	0
1	181	188	982
2	115	129	118
3	136	147	987
4	138	160	852
5	168	156	97
6	119	142	843
7	86	73	791
8	150	164	86
9	152	175	951
10	154	171	6
11	92	99	81
12	146	158	951
13	119	97	134
14	112	134	169
15	128	145	137
16	94	101	759
17	111	106	40
18	96	98	825
19	50	27	988
20	76	74	40
21	29	18	180
1,6,L			
0	98	102	0
1	118	92	34
2	110	120	990
3	137	164	225
4	140	140	166
5	189	218	65
6	80	50	975
7	112	118	900
8	101	98	791
9	53	87	802
10	54	58	810
11	168	188	18
12	64	74	949
13	133	152	44
14	84	86	768
15	49	57	90
16	40	49	198
17	47	39	819
18	43	35	780
1,7,L			
0	130	118	500
1	62	69	194
2	93	64	21
3	101	121	933
4	80	69	20
5	112	131	27
6	75	45	91
7	97	119	65
8	48	44	23
9	118	140	15
10	86	95	47
12	73	102	992
13	40	17	155
14	50	37	957
2,0,L			
0	492	499	0
2,1,L			
0	660	702	0
1	699	657	959
2	511	522	859
3	343	343	41
4	258	261	949
5	242	173	163
6	364	373	52
7	133	119	791
8	266	286	982
9	452	472	887
10	231	249	219
11	187	160	78
12	347	397	4
13	183	149	203
14	153	159	987
15	112	100	988
16	186	186	969
17	153	151	852
18	88	89	33
19	138	128	140
20	122	110	50
21	63	36	807
22	84	87	860
23	68	44	80
24	137	132	925
25	57	26	92
2,2,L			
0	317	287	500
1	87	70	932
2	566	549	6
3	311	288	861
4	158	136	975
5	321	275	147
6	111	121	909
7	149	133	34
8	299	287	849
9	84	77	152
10	447	450	979
11	150	142	216
12	77	64	887
13	133	122	39
14	275	290	27
15	129	125	921
16	193	191	194
17	96	95	113
18	48	68	843
19	71	64	984
20	44	42	95
21	60	40	125
22	173	178	956
23	40	40	893
24	56	42	993
25	24	17	777
2,3,L			
0	370	344	0
1	241	245	897
2	96	82	989
3	200	200	941
4	216	230	35
5	315	313	821
6	162	147	794
7	207	202	32
8	209	165	245
9	175	183	961
10	168	170	143
11	235	264	193
12	243	239	944
13	220	217	793
14	131	133	909
15	161	151	233
16	265	274	971
17	46	38	966
18	53	34	178
19	88	79	104
20	57	24	141
21	83	82	211
22	84	69	794
23	107	97	150
24	162	168	866
2,4,L			
0	168	154	500
1	366	386	19
2	228	240	26
3	237	211	852
4	163	176	250
5	74	52	200
6	147	128	245
7	277	309	925
8	86	80	64
9	184	184	1
10	112	115	894
11	210	209	828
12	75	32	219
13	100	71	191
14	74	69	98
15	109	92	807
16	52	44	940
17	100	89	911
18	74	50	982
19	79	80	755
20	58	55	868
21	76	87	90
22	74	90	14
2,5,L			
0	189	179	500
1	43	41	918
2	156	148	70
3	239	243	197
4	85	67	991
5	105	98	827
6	185	189	210
7	198	220	143
8	106	108	1
9	69	54	966
10	142	163	198
11	100	106	160
12	135	142	15
13	63	43	117
14	22	21	842
15	198	228	110
16	33	25	96
17	97	93	992
18	36	37	55
19	63	58	114
20	81	86	971
2,6,L			
0	43	22	500
1	124	141	886
2	183	181	965
3	236	235	4
4	53	57	759
5	69	67	931
6	19	18	854
7	91	84	232
8	47	27	821
9	102	77	951
10	117	112	900
11	136	148	932
12	71	69	205
13	82	55	20
14	114	92	911
15	71	62	781
16	45	38	184
17	59	35	142
2,7,L			
0	41	15	500
1	153	161	1000
2	89	81	929
3	65	84	820
4	84	53	838
5	60	33	814
6	106	103	831
7	141	143	42
8	66	54	218
9	101	110	977
10	58	36	79
11	92	79	16
12	70	52	855
13	81	84	995
3,0,L			
0	47	14	500
16	109	106	38
17	83	91	992
18	182	185	822
19	60	73	856
20	58	76	82
21	104	112	954
22	134	193	51
23	68	73	[illegible]
24	51	20	[illegible]
25	77	83	870
3,1,L			
0	192	195	0
1	152	103	810
2	284	265	870
3	241	244	801
4	264	248	33
5	233	245	932
6	239	247	814
7	140	129	81
8	121	52	17
9	174	93	9
10	110	86	4
11	244	244	18
12	219	231	94
13	109	98	89
14	234	247	87
15	107	93	79
16	151	118	78
17	114	116	90
18	151	137	80
19	158	175	12
20	98	81	95
21	97	107	92
22	78	78	89
23	52	33	11
24	62	45	76
25	102	93	14
3,2,L			
0	475	479	50
1	164	158	25
2	179	205	18
3	172	158	89
4	228	212	84
5	263	230	14
6	146	135	10
7	261	254	82
8	377	385	6
9	92	52	90
10	198	230	7
11	107	75	95
12	257	248	94
13	171	160	11
14	172	187	99
15	190	191	17
16	166	135	
17	76	78	99
18	64	79	
19	119	144	24
20	129	131	91
21	44	30	13
22	111	108	88
23	112	112	90
24	96	54	19
3,3,L			
0	432	433	50
1	296	293	19
2	135	147	90
3	132	114	77
4	226	244	20
5	192	188	6
6	169	161	77
7	18	21	82
8	337	348	89
9	175	171	22
10	77	72	10
11	113	109	89
12	193	196	10
13	257	243	6
14	91	98	75
15	134	122	83
16	214	210	75
17	207	173	89
18	110	104	15
19	86	63	1
20	133	123	99
21	94	86	14
22	54	32	8
23	102	95	80
3,4,L			
0	45	19	
1	127	99	85
2	129	101	76
3	387	410	99
4	106	91	80
5	176	169	98
6	93	90	22
7	151	163	83
8	75	42	84
9	125	133	9
10	142	148	4
11	262	277	95
12	50	50	80
13	92	66	6
14	114	126	7
15	145	142	87
16	90	76	84
17	116	111	14
18	77	96	77
19	70	70	86
20	44	16	82
21	97	92	3
3,5,L			
0	157	166	
1	165	176	58
2	120	118	927
3	89	77	943
4	72	44	33
5	136	155	99
6	153	147	182
7	97	94	942
8	134	105	932
9	54	27	817
10	174	186	41
11	107	99	882
12	69	56	946
13	144	168	14
14	85	75	861
15	52	28	97
16	88	33	852
17	122	114	974
18	47	43	992
19	45	43	998
3,6,L			
8	116	109	83
9	97	92	36
11	52	64	754
12	65	61	994
13	50	29	195
14	100	78	43
15	51	42	217
3,7,L			
3	63	47	8
4	136	138	187
6	24	28	43
4,0,L			
0	330	330	500
4,1,L			
0	233	193	500
1	379	402	98
2	263	224	23
3	435	477	813
4	215	182	762
5	304	314	216
6	80	67	166
7	69	36	28
8	267	266	837
9	318	359	108
10	162	159	954
11	274	289	778
12	108	68	154
13	88	51	29
14	148	138	955
15	188	196	250
16	178	183	761
17	141	149	22
18	38	30	898
19	48	15	207
20	97	74	856
21	80	84	220
22	85	84	891
23	51	34	143
4,2,L			
0	242	222	0
1	339	346	928
2	182	162	208
3	318	329	97
4	164	161	873
5	153	162	249
6	157	142	236
7	185	182	947
8	94	80	47
9	217	251	833
10	100	101	26
11	260	272	59
12	173	189	892
13	196	200	951
14	71	52	839
15	182	205	192
16	87	102	847
17	117	118	936
18	130	135	902
19	94	100	910
20	45	37	246
21	80	63	889
22	48	23	775
4,3,L			
0	85	96	500
1	171	174	125
2	208	214	972
3	218	152	91
4	134	124	755
5	244	248	190
6	81	60	233
7	124	114	837
8	141	154	855
9	56	46	87
10	171	169	999
11	192	172	869
12	59	55	40
13	183	204	110
14	90	75	923
15	89	63	101
16	129	123	765
17	75	64	242
18	72	73	985
19	81	58	895
20	94	80	782
21	81	91	956
4,4,L			
0	416	432	0
1	261	272	829
2	113	122	183
3	53	33	772
4	137	142	866
5	157	167	829
6	180	195	792
7	254	266	99
8	230	250	921
9	52	44	773
10	82	90	947
11	154	160	58
12	177	174	898
13	87	84	762
14	118	129	202
15	74	83	60
16	82	88	111
17	51	29	873
18	99	96	753
19	65	77	22
20	63	55	782
4,5,L			
0	47	29	500
1	144	158	30
2	124	127	46
3	68	48	910
4	162	158	774
5	64	29	795
6	64	59	173
7	76	72	926
8	86	86	783
9	112	119	975
10	64	65	907
11	29	23	209
12	66	64	806
13	96	95	135
14	59	39	869
15	76	55	225
16	119	123	833
17	58	55	846
4,6,L			
0	46	42	500
1	87	80	759
2	125	123	867
3	189	198	197
4	88	30	824
5	97	70	781
6	150	154	234
7	12	13	181
8	69	58	85
9	75	72	854
10	77	66	83
11	179	187	100
12	67	51	995
13	62	24	60
4,7,L			
0	103	121	500
2	70	79	965
3	89	76	917
4	78	61	21
5	76	81	130
6	59	64	946
7	52	54	924
5,0,L			
0	125	125	0
5,1,L			
0	200	181	0
1	174	160	193
2	112	108	976
3	67	48	167
4	72	53	967
5	249	276	237
6	68	48	890
7	180	200	881
8	111	95	883
9	64	27	839
10	96	78	994
11	105	118	808
12	105	110	897
13	186	203	159
14	63	69	123
15	137	142	876
16	77	71	963
17	90	79	130
18	49	34	974
19	96	111	768
20	53	44	185
21	56	38	106
5,2,L			
0	174	182	0
1	52	73	67
2	254	294	883
3	163	153	74
4	144	143	129
5	139	167	906
6	207	226	136
7	173	169	174
8	87	91	907
9	109	120	860
10	110	123	893
11	63	60	159
12	109	111	36
13	89	99	955
14	47	59	225
15	93	56	147
16	31	40	816
17	94	104	893
18	47	41	770
19	56	40	939
20	75	89	12
5,3,L			
0	79	40	0
1	108	99	988
2	54	31	773
3	150	151	11
4	161	151	842
5	96	88	17
6	113	118	250
7	93	74	774
8	204	226	795
9	89	103	12
10	96	65	178
11	139	151	892
12	89	88	956
13	75	50	873
14	77	90	144
15	93	87	6
16	187	191	754
17	110	112	942
18	76	83	91
19	84	72	219
5,4,L			
0	79	81	500
1	61	19	39
2	136	129	888
3	102	121	243
4	80	65	213
5	120	129	836
6	125	130	223
7	95	89	798
8	91	87	872
9	100	111	832
10	94	90	47
11	77	95	229
12	72	86	85
13	82	73	882
14	92	99	894
15	132	150	779
16	79	73	151
17	98	107	817
5,5,L			
0	69	23	0
1	46	51	155
2	120	116	65
3	164	181	795
4	85	96	134
5	141	143	206
6	92	86	766
7	117	117	871
8	58	55	826
9	89	102	118
10	97	93	934
11	50	71	61
12	87	84	24
13	93	96	753
14	55	51	115
5,6,L			
0	44	35	500
1	133	149	26
2	37	41	870
3	52	17	872
4	60	73	200
5	82	89	966
6	60	79	825
7	84	103	960
8	60	76	246
9	82	73	996
6,0,L			
0	192	204	0
1	161	182	87
2	184	184	939
3	92	91	805
4	152	161	212
5	45	47	53
6	89	77	142
7	121	124	829
8	197	204	890
9	29	28	977
10	124	125	983
11	119	124	777
12	108	122	63
13	51	52	179
14	83	97	961
15	42	31	949
16	119	122	776
17	57	41	154
18	36	41	811
6,1,L			
0	162	135	500
1	177	182	923
2	153	180	793
3	117	122	846
4	180	165	792
5	122	81	249
6	176	191	173
7	114	90	155
8	129	120	97
9	84	96	798
10	71	83	171
11	82	39	223
12	140	140	923
13	73	53	185
14	137	144	92
15	105	114	209
16	73	78	901
17	46	32	43
18	49	35	852
6,2,L			
0	49	37	0
1	91	54	171
2	224	242	6
3	181	161	821
4	73	51	756
5	80	69	180
6	29	24	781
7	105	107	751
8	80	76	80
9	132	128	174
10	189	201	947
11	90	69	817
12	60	63	973
13	51	56	33
14	144	129	942
15	79	81	216
16	19	19	56
17	78	74	239
6,3,L			
0	94	63	0
1	187	174	869
2	140	116	119
3	76	83	30
4	71	48	814
5	79	73	816
6	201	180	812
7	71	56	182
8	56	17	161
9	104	90	812
10	97	86	897
11	87	67	97
12	64	51	101
13	123	128	834
14	125	113	760
15	76	66	939
6,4,L			
0	25	23	0
1	147	141	181
2	67	38	231
3	93	62	115
4	197	225	205
5	131	130	87
6	76	77	772
7	34	37	245
8	107	115	161
9	48	37	5
10	41	20	82
11	93	65	96
12	57	52	66
13	104	108	19
6,5,L			
0	111	133	0
1	67	34	902
2	66	61	903
3	76	82	191
4	58	62	941
5	77	62	838
6	39	42	48
7	78	85	217
8	62	60	976
9	92	94	812
7,0,L			
0	121	120	0
1	86	84	859
2	142	150	999
3	135	153	919
4	80	80	934
5	71	74	197
6	38	13	235
7	99	105	809
8	47	53	152
10	115	133	914
11	66	84	885
12	64	69	972
13	73	83	225
14	67	56	874
7,1,L			
0	115	103	500
1	87	74	859
2	90	97	208
3	80	59	119
4	82	59	138
5	76	37	764
6	196	205	247
7	62	32	98
8	75	94	756
9	100	84	857
10	93	86	204
11	21	29	114
12	64	23	766
13	81	75	955
14	106	92	207
7,2,L			
0	101	105	0
1	131	129	146
2	63	56	819
3	68	54	134
4	109	113	814
5	131	137	225
6	64	57	106
7	118	112	765
8	37	24	19
9	75	70	907
10	44	31	198
11	70	51	808
12	59	61	215
13	87	82	153
7,3,L			
0	44	21	500
1	41	44	751
2	64	70	988
3	136	120	190
4	80	47	766
5	127	141	790
7	149	136	165
8	47	42	13
9	93	90	796
10	47	41	960
11	60	23	863
7,4,L			
0	44	56	0
1	36	25	43
2	36	32	945
3	82	86	3
4	94	103	229
5	49	42	997
6	72	75	868
7	53	32	28

full-matrix least-squares refinement was continued until the R index converged to 0·097. The average shift/estimated standard deviation was below 0·24, and the goodness-of-fit $[\sum w(F_o-F_c)^2/m-s]^{1/2}$ was 3·1. The final non-hydrogen parameters with estimated standard deviations are given in Table 2, and the hydrogen positions are given in Table 3. The final observed and calculated structure factors are listed in Table 4.

Examination of the final atomic coordinates suggested that the two halves of the cystine molecule were nearly related by a twofold axis of symmetry running through the midpoint of the S(1)–S(2) bond. The same situation was observed for dibenzyl disulfide (Lee & Bryant, 1969). During the final cycles of cystine refinement, several parameters were observed to shift by as much as 80% of their estimated standard deviation. The correlation matrix showed some degree of correlation (0·10 to 0·20) between the S(1) and S(2) parameters. There were also slight parameter correlations between the C(1)–C(4), C(2)–C(5), C(3)–C(6), N(1)–N(2), O(1)–O(3), and O(2)–O(4) atom pairs.

Since the $h00$ extinctions were not conclusive, other tests were used to determine the correct space group (a choice between $P4_1$ and $P4_12_12$).

One of the tests used to differentiate between space groups was the calculation of an agreement index ($R'=\sum||F_{hkl}|-|F_{\bar{h}kl}||/\sum|F_{hkl}|$). The space group $P4_12_12$ requires that $|F_{hkl}|\equiv|F_{\bar{h}kl}|$, while $P4_1$ does not. The $k=0$ level served as a basis for comparison, since the $h0l$ and $\bar{h}0l$ levels are equivalent for both space groups. The results, which are presented in Table 5, show the $k=0$ agreement value to be significantly lower than the upper-level values.

Table 5. *Agreement values (R') between the hkl and $\bar{h}$kl levels*

Level k	R'
0	0·0394
1	0·189
2	0·168
3	0·198
4	0·226
5	0·226

Statistical averages (Karle, Dragonette & Brennen, 1966) also were calculated for the $h0l$ and $h1l$ levels of data. The $h0l$ level is required to be centrosymmetric for $P4_12_12$ and non-centrosymmetric for $P4_1$, while the $h1l$ level is non-centrosymmetric for both space groups. The averages, which are presented in Table 6, indicate that the $h0l$ and $h1l$ levels are closer to being non-centrosymmetric.

As a final test, the structure was further refined by full-matrix least-squares calculations in both space groups $P4_1$ and $P4_12_12$, and the final R indices after convergence were compared. The values obtained were 0·330 and 0·097, respectively. The rather short intermolecular contact of 3·10 Å, observed between C(5) and O(4), helped explain the difficulty of refining in $P4_12_12$. It appears that the major objection to placing the sulfur atoms across a crystallographic twofold axis is the steric interaction between glycine-like groups on adjacent molecules.

Table 6. *Statistical tests on the h0l and h1l levels*

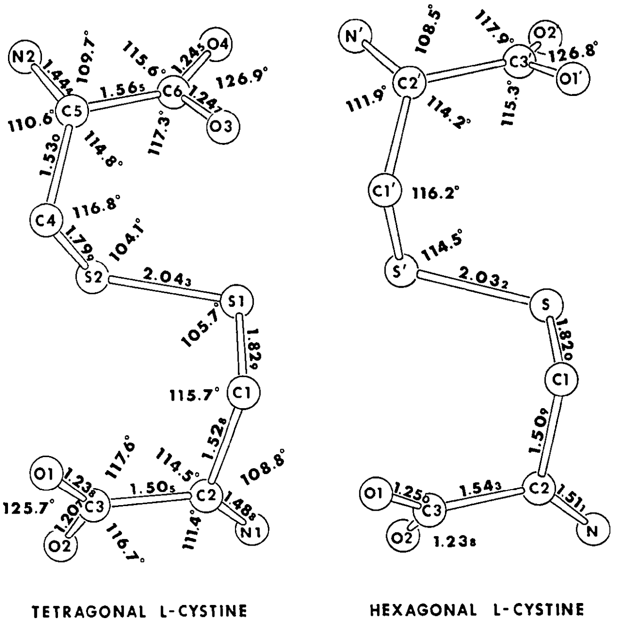
	Level	$\langle\|E\|\rangle$	$\langle\|\|E\|^2-1\|\rangle$
Observed	$h0l$	0·907	0·719
	$h1l$	0·957	0·569
Theoretical	Level	$\langle\|E\|\rangle$	$\langle\|\|E\|^2-1\|\rangle$
	Acentric	0·886	0·736
	Centric	0·798	0·968

It was concluded from the above results that the tetragonal form of L-cystine contains almost, but not quite, a twofold axis of symmetry. $P4_1$ was assigned as the most probable space group for tetragonal L-cystine.

Discussion

Covalent bond lengths and angles for tetragonal (TLC) and hexagonal L-cystine (HLC) (Oughton & Harrison, 1959) are shown in Fig. 2. Each half of the TLC molecule is related by a pseudo-twofold axis of symmetry. A comparison of related covalent bond lengths shows an equivalence, usually within two standard deviations, while related intermolecular distances differ as much as 36 standard deviations [S(2)···C(1), 3·61 (1) Å; and S(1)···C(4), 3·97 (1) Å]. The above and other related intermolecular distances indicate that most of the molecule's deviation from twofold symmetry occurs at the β-carbons, C(1) and C(4).

When the covalent bond lengths and angles for TLC



TETRAGONAL L-CYSTINE HEXAGONAL L-CYSTINE

Fig. 2. Tetragonal and hexagonal (Oughton & Harrison, 1959) L-cystine. A comparison of covalent bond lengths, angles, and conformation. The estimated standard deviations for tetragonal L-cystine vary from 0·006 Å for the S–S distances to 0·019 Å for the C–C distances and from 0·5° for the S–S–C angles to 1·0° for the C–C–C angles.

are compared with those of HLC, all except the sulfur valence angles are equivalent within experimental error. The average sulfur valence angle for TLC is 105·2 (6)°, which is significantly different from 114·5 (4)° for HLC. In fact, this value for HLC is significantly different from the average value 103·6 (11)° for all other structurally determined L-cystine compounds to date (Chaney, 1969).

The molecules of TLC are held together by a network of hydrogen bonds. A molecular packing diagram (Fig. 3) drawn by *ORTEP* (Johnson, 1965) shows the hydrogen-bonding arrangement and distances. The approximate tetrahedral arrangement of hydrogen-bonded oxygen atoms about the amino nitrogens and equivalent carboxyl C–O bond lengths indicate that both TLC and HLC exist in their zwitterion form. Again, TLC's deviation from crystallographic twofold symmetry is apparent from its non-equivalent hydrogen bonding. The N(1)· · ·O(4) [2·79 (2) Å] and N(2)· · ·O(2) [2·90 (2) Å] hydrogen bonds, related by the pseudo-twofold axis, deviate by more than five standard deviations. Both TLC and HLC are found to have the same average hydrogen-bonding distance of 2·82 Å, suggesting that both crystal forms are equally stabilized by hydrogen bonding.

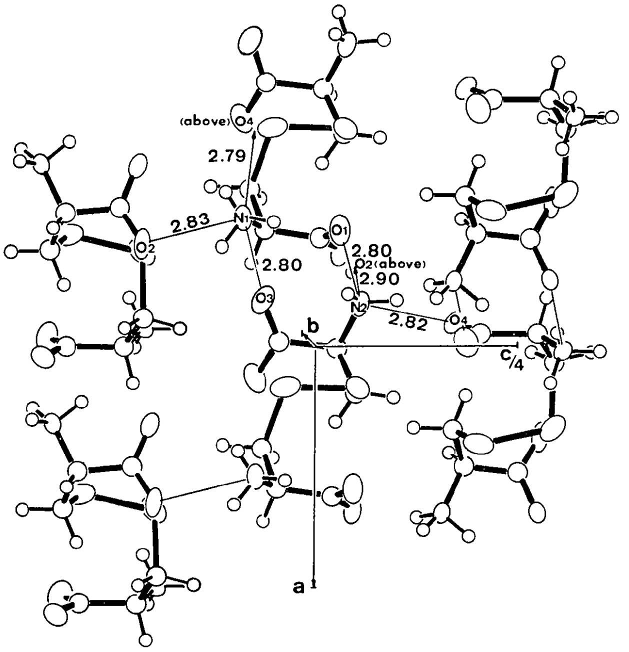


Fig. 3. A molecular packing diagram of tetragonal L-cystine. The estimated standard deviations for hydrogen-bond distances vary from 0·01 to 0·02 Å.

The mean-plane equations and atomic deviations for the glycine-like groups of TLC are listed in Table 7. None of the atoms included in the calculation deviated significantly from their respective mean planes. The amino nitrogens, N(1) and N(2), are observed to deviate by 0·148 and −0·131 Å, respectively.

The molecular conformations of TLC and HLC are similar, as shown in Fig. 2. Both molecules are observed to have a right-handed disulfide chirality (see Fig. 1). An obvious difference in the two conformations is the dihedral angle between the planes of the glycine-like groups on one molecule. For TLC, this dihedral angle is 60·9°, which is significantly different from that of 12·0° for HLC. Another conformational difference is the disulfide dihedral angle [C(4)–S(2)–S(1)–C(1)], which is 69·3° for TLC and 74° for HLC.

The observed molecular conformations of cystine are influenced by the packing forces within the crystal. When the two crystalline-state conformations are compared, we find that most of the conformational differences are at the ends of the molecule, as observed from the dihedral angles between glycine-like groups. This angle for TLC is expected to be close to 90°, since the direction of hydrogen bonding is mostly perpendicular to the crystal's fourfold symmetry. However, for HLC, its hydrogen bonding is in a direction almost parallel to the crystal's sixfold axis, and the glycine-like group dihedral angle is expected to be near 0°. It is interesting to observe that although the glycine-like group dihedral angles differ greatly between conformational states, the disulfide dihedral angles are relatively close in value. It would appear that cystine's confor-

Table 7. *Least-squares planes and atomic deviations* (Å)

All equations are expressed in orthogonal Ångström space.

I. Equation through atoms C(2), C(3), O(1) and O(2)

$$0{\cdot}938x-0{\cdot}305y-0{\cdot}166z=2{\cdot}69$$

Standard deviation of atoms from plane =0·008 Å

C(2)	−0·003
C(3)	0·011
O(1)	−0·004
O(2)	−0·004
N(1)	0·148

II. Equation through atoms C(5), C(6), O(3) and O(4)

$$-0{\cdot}192x+0{\cdot}980y+0{\cdot}042z=6{\cdot}93$$

Standard deviation of atoms from plane =0·010 Å

C(5)	0·004
C(6)	−0·015
O(3)	0·006
O(4)	0·006
N(2)	−0·131

III. Equation through atoms S(2), S(1) and C(1)

$$-0{\cdot}246x+0{\cdot}948y-0{\cdot}200z=3{\cdot}75$$

IV. Equation through atoms S(1), S(2) and C(4)

$$0{\cdot}993x-0{\cdot}115y-0{\cdot}002z=0{\cdot}495$$

Angle between planes I and II = 60·9°
Angle between planes III and IV = 69·3°

mational flexibility is a result of the carboxyl groups rotating about the C(2)–C(3) and C(5)–C(6) bonds; the amount of rotation depending upon the packing requirements of its nearest neighbors. Similarly, if L-cystine was present in a polypeptide or protein, we would expect its specific conformation to be dependent upon the polypeptide's or protein's backbone conformation.

The authors wish to acknowledge support from the National Science Foundation (Grant GB3807). They are also indebted to Indiana University Medical Center for making computer facilities available, and to the Heart Research Center (Grant HE06308) and U. S. Public Health Service for their support.

References

Busing, W. R., Martin, K. O. & Levy, H. A. (1962). *ORFLS*. Report ORNL-TM-305, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Chaney, M. O. (1969). Ph. D. Thesis, Indiana Univ., 122.

Chaney, M. O. & Steinrauf, L. K. (1968). *Acta Cryst.* **B24**, 1564–1567.

International Tables for X-ray Crystallography (1962). Vol. III, p. 202. Birmingham: Kynoch Press.

Johnson, C. K. (1965). *ORTEP*. Report ORNL-3794, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Karle, I. L., Dragonette, K. S. & Brenner, S. A. (1965). *Acta Cryst.* **19**, 713–716.

Lee, J. D. & Bryant, M. W. R. (1969). *Acta Cryst.* **B25**, 2497–2504.

Oughton, B. M. & Harrison, P. M. (1959). *Acta Cryst.* **12**, 396–404.

Peterson, J., Steinrauf, L. K. & Jensen, L. H. (1960). *Acta Cryst.* **13**, 104–109.

Pinkerton, J. M. H. & Steinrauf, L. K. (1967). *J. Org. Chem.* **32**, 1828–1832.

Steinrauf, L. K., Peterson, J. & Jensen, L. H. (1958). *J. Amer. Chem. Soc.* **80**, 3835–3838.

World List of Crystallographic Computer Programs (1966). 2nd ed. Utrecht: Oosthoek.

Yakel, H. L. & Hughes, E. W. (1954). *Acta Cryst.* **7**, 291–297.

Acta Cryst. (1974). B**30**, 716

Structure Cristalline du Complexe Cobalt (Imidazole)$_6$ (Acétate)$_2$ Monohydraté

PAR ALAIN GADET ET ODETTE LEFEBVRE SOUBEYRAN

Laboratoire de Cristallochimie, Tour 44, 11 *quai Saint Bernard*, 75005 *Paris, France*

(*Reçu le* 3 *septembre* 1973, *accepté le* 5 *novembre* 1973)

The $Co(Im)_6(Ac)_2.H_2O$ complex crystallizes in the triclinic system, space group $P\bar{1}$, with one 'molecule' in the unit cell. The unit-cell constants are: $a=8{\cdot}48$, $b=10{\cdot}05$, $c=8{\cdot}81$ Å, $\alpha=90{\cdot}0$, $\beta=82{\cdot}3$, $\gamma=94{\cdot}0°$. 1600 reflexions have been collected by photographic methods on a Weissenberg goniometer and the structure has been solved by the heavy-atom method ($R=0{\cdot}095$). One water molecule is present in the unit cell and is able to occupy statistically two centrosymmetric positions. The ligands are imidazole groups. The coordination polyhedron is octahedral and does not show significant deformation with respect to a regular octahedron. The ligands do not all have the same orientation. A three-dimensional hydrogen-bond network exists between ligands and the water molecule or acetate groups.

Introduction

L'étude structurale du complexe hydraté $Co(Im)_6(Ac)_2.H_2O$ a été abordée à la suite du complexe $Co(Im)_2(Ac)_2$ (Gadet, 1974). Ce dernier ne conserve sa structure tétraédrique que dans les solvants organiques purs ou additionnés de peu d'eau. Un grand pourcentage d'eau le transforme en complexe octaédrique par addition de molécule d'eau (Dobry-Duclaux & May, 1970).

Le complexe $Co(Im)_6(Ac)_2$ obtenu à partir d'une solution aqueuse est un complexe octaédrique qui fait intervenir les mêmes groupements chimiques que le complexe $Co(Im)_2(Ac)_2$. Le travail présenté ici concerne la description de sa structure cristalline, les premiers

Tableau 1. *Données cristallographiques et physiques*

Formule brute: $C_{22}H_{30}O_4N_{12}Co.H_2O$
Système cristallin: triclinique
Groupe spatial: $P\bar{1}$, mais $P1$ est plausible.

$a=$ 8,48 (5) Å
$b=$10,05 (7)
$c=$ 8,81 (5)
$\alpha=$90,0 (5)°
$\beta=$82,3 (5)
$\gamma=$94,0 (5)
$V=$742 Å^3
$Z=1$

$D_c=1{,}35$ g cm^{-3} avec une molécule d'eau
1,39 g cm^{-3} avec deux molécules d'eau
$D_m=1{,}37$ g cm^{-3}
Radiation utilisée: Co $K\bar{\alpha}$($\lambda=1{,}7902$ Å)