

The Crystal Structure of L-Valine

BY KAZUO TORII AND YOICHI IITAKA

Faculty of Pharmaceutical Sciences, University of Tokyo, Hongo, Tokyo, Japan

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The crystal structure of L-valine has been determined by X-ray diffraction methods. L-valine crystallizes in the monoclinic space group $P2_1$, $Z=4$, with lattice constants $a=9.71$, $b=5.27$, $c=12.06$ Å, $\beta=90.8^\circ$. Final refinement was carried out for 960 observed structure factors by the full-matrix least-squares method including anisotropic thermal parameters. The R value was 0.126. The asymmetric unit contains two crystallographically independent molecules, which are shown to have different conformations about the $C_\alpha-C_\beta$ bond. The molecules are held together by hydrogen bonds to form a double-layer structure. The side chains are packed together in a manner resembling that in the $O\perp$ packing of long chain hydrocarbons, and this may account for the different conformations of the two molecules.

Introduction

In the course of a study on the infrared absorption spectra of amino acids, Tsuboi, Takenishi & Iitaka (1959) found that the crystal of L-valine gives a spectrum quite different from that of the crystal of DL-valine. The latter crystal gives absorption bands which can be assigned to the expected vibrational modes for the valine molecule with a certain definite conformation, while the former crystal gives extra bands which are situated too far from the expected positions to be explained by the splitting of bands due to the crystalline field. On the basis of these findings, they suggested that the L-valine crystal belongs to a rather unusual type of crystal, which is composed of molecules which belong to one species but with two kinds of conformation. To confirm this suggestion and to determine accurate molecular conformations, an X-ray crystal structure analysis of L-valine was carried out.

Experimental

Crystals of L-valine were grown from a warm saturated aqueous solution by slow cooling. They are colourless thin flakes elongated along the b axis with well developed $\{001\}$ faces.

Crystal data

L-Valine, $C_5H_{11}O_2N$, molecular weight: 117.2.
 Monoclinic
 $a=9.71 \pm 0.01$, $b=5.27 \pm 0.02$, $c=12.06 \pm 0.02$ Å,
 $\beta=90.8^\circ \pm 0.2^\circ$
 $U=617.2$ Å³
 $D_m=1.263$ g.cm⁻³, $D_x=1.261$ g.cm⁻³.
 $Z=4$
 Systematic absences, $0k0$ when $k \neq 2n$
 Space group, $P2_1$.

The unit-cell dimensions were obtained from measurements on precession photographs. Three-dimensional intensity data were collected from equi-inclination

Weissenberg photographs taken with Cu $K\alpha$ radiation on multiple-film packs. Intensities were measured by the use of a photometer and partly by visual comparison with a calibrated intensity scale. They were corrected for Lorentz, polarization and spot-shape (Phillips, 1954) factors but no absorption correction was applied. These intensity data were scaled by correlating various layers and the mean temperature factors were calculated by Wilson's (1942) method.

Intensity data

a axis: 0 to 5th layer

b axis: 0 to 3rd layer

Total number of independent observed structure factors: 960 (out of 1346 possible reflexions with $\theta < 80^\circ$)

Mean temperature factor by Wilson's method: 2.37 Å².

Determination and refinement of the structure

The two-dimensional Patterson projection map (u, w) is shown in Fig. 1, which indicates four zones of peaks, A, B, C and D , arranged parallel to the (001) plane. The separation of A and B zones and that of B and C are found to be about 2.8 and 3.2 Å respectively, suggesting that the structure of the present crystal may be composed of double layers of molecules. A similar double-layer structure has often been found in crystals of amino acids. As shown below, the crystal of L-cysteine (Harding & Long, 1968) possesses very similar lattice constants and identical space group to those of the present crystal if the a and c axis are interchanged:

L-valine, $a=9.71$, $b=5.27$, $c=12.06$ Å, $\beta=90.8^\circ$,
 $P2_1$, $Z=4$;

L-cysteine, $a=11.51$, $b=5.24$, $c=9.52$ Å, $\beta=109^\circ 8'$,
 $P2_1$, $Z=4$.

Approximate positions of the atoms other than C_γ were therefore obtained by assuming fractional coordinates similar to those for the atoms in L-cysteine for the

present crystal lattice. The correctness of this model of the structure was confirmed by a three-dimensional Patterson map. A three-dimensional electron density map was then calculated with the use of phase angles determined from the atoms O(1), O(2), N(1), O(11), O(12) and N(11), which gave an R value of 0.39. The structure of the molecule, except for the terminal C_γ atom, was determined from this map. At this stage, refinement of positional and isotropic thermal parameters of six atoms for each molecule was carried out by the block-matrix least-squares method. The R value was reduced to 0.29. A subsequent difference Fourier synthesis revealed the positions of the two C_γ atoms for each molecule.

Refinement of the structure was continued by the block-matrix least-squares method, and the R value decreased to 0.15. Another five cycles of refinement by the block-matrix least-squares method, including anisotropic thermal parameters, reduced R to 0.13. Finally, two cycles of full-matrix least-squares refine-

ment along the same lines were carried out using the program *ORFLS* (Busing, Martin & Levy, 1962). The final R value was 0.126 excluding unobserved structure factors. In this calculation the following weighting scheme was adopted;

$$\begin{aligned} \sqrt{w} &= F_o/7.0, & \text{when } F_o \leq 7.0, \\ \sqrt{w} &= 7.0/F_o, & \text{when } 7.0 < F_o \leq 40.0, \\ \sqrt{w} &= 7.0 \times 40.0/F_o^2, & \text{when } 40.0 < F_o. \end{aligned}$$

None of the shifts in the final cycle was greater than one-quarter of the standard deviations and the refinement was considered to be complete. A difference Fourier synthesis was calculated, but it was not possible to determine the positions of the hydrogen atoms with certainty. The final atomic parameters are listed in Table 1 along with their estimated standard deviations. Comparisons of the observed and calculated structure factors are given in Table 2. In the present study, the atomic scattering factors given by Berghuis,

Table 1. Final atomic parameters and their standard deviations

For L-molecules the coordinates refer to the right-handed system. The temperature factors are in the form

$$T = \exp [- (\beta_{11}h^2 + \beta_{22}k^2 + \beta_{33}l^2 + 2\beta_{12}hk + 2\beta_{13}hl + 2\beta_{23}kl)].$$

Molecule A									
	x	y	z	β_{11}	β_{22}	β_{33}	β_{12}	β_{13}	β_{23}
O(1)	0.8705 (6)	1.0167 (0)	0.3996 (6)	0.0053 (7)	0.0196 (26)	0.0070 (6)	0.0012 (13)	0.0001 (5)	-0.0014 (11)
O(2)	0.7916 (7)	0.6466 (20)	0.3367 (7)	0.0064 (7)	0.0185 (27)	0.0068 (6)	0.0008 (13)	-0.0014 (6)	0.0008 (11)
N(1)	0.6247 (8)	1.2332 (21)	0.4116 (7)	0.0058 (8)	0.0181 (30)	0.0050 (6)	0.0014 (14)	-0.0010 (6)	-0.0009 (11)
C(1)	0.7766 (10)	0.8770 (24)	0.3635 (8)	0.0068 (11)	0.0183 (39)	0.0046 (7)	0.0019 (18)	-0.0000 (7)	0.0020 (13)
C(2)	0.6351 (9)	0.9938 (23)	0.3457 (9)	0.0051 (9)	0.0137 (31)	0.0064 (8)	-0.0018 (18)	0.0004 (7)	0.0001 (14)
C(3)	0.5975 (10)	1.0412 (26)	0.2224 (8)	0.0072 (10)	0.0187 (34)	0.0048 (8)	0.0013 (17)	-0.0023 (7)	-0.0014 (13)
C(4)	0.5426 (14)	0.8002 (31)	0.1658 (13)	0.0128 (15)	0.0286 (52)	0.0093 (12)	-0.0043 (27)	-0.0040 (11)	-0.0056 (20)
C(5)	0.7243 (13)	1.1525 (32)	0.1597 (10)	0.0122 (15)	0.0363 (55)	0.0054 (8)	0.0018 (27)	0.0024 (10)	0.0019 (19)
Molecule B									
	x	y	z	β_{11}	β_{22}	β_{33}	β_{12}	β_{13}	β_{23}
O(11)	0.3549 (7)	0.4169 (21)	0.3963 (7)	0.0056 (7)	0.0183 (25)	0.0077 (6)	0.0034 (12)	0.0005 (5)	-0.0013 (10)
O(12)	0.2736 (8)	0.0249 (19)	0.3700 (7)	0.0094 (9)	0.0125 (26)	0.0082 (7)	0.0012 (14)	-0.0015 (6)	0.0023 (11)
N(11)	0.0878 (9)	0.5988 (22)	0.3748 (9)	0.0069 (9)	0.0201 (36)	0.0076 (7)	0.0038 (16)	-0.0011 (7)	-0.0015 (13)
C(11)	0.2634 (9)	0.2594 (25)	0.3632 (10)	0.0041 (9)	0.0182 (36)	0.0071 (9)	0.0023 (18)	0.0011 (7)	-0.0001 (14)
C(12)	0.1336 (10)	0.3752 (21)	0.3083 (9)	0.0059 (9)	0.0100 (31)	0.0067 (8)	0.0021 (15)	-0.0010 (7)	0.0022 (13)
C(13)	0.1668 (10)	0.4563 (24)	0.1911 (9)	0.0071 (10)	0.0183 (37)	0.0061 (9)	0.0027 (19)	-0.0006 (8)	0.0007 (14)
C(14)	0.0379 (13)	0.5770 (32)	0.1345 (10)	0.0121 (15)	0.0463 (67)	0.0049 (8)	0.0071 (26)	-0.0028 (9)	0.0041 (18)
C(15)	0.2158 (16)	0.2332 (35)	0.1215 (11)	0.0156 (18)	0.0441 (63)	0.0064 (10)	0.0114 (32)	0.0016 (11)	-0.0006 (22)

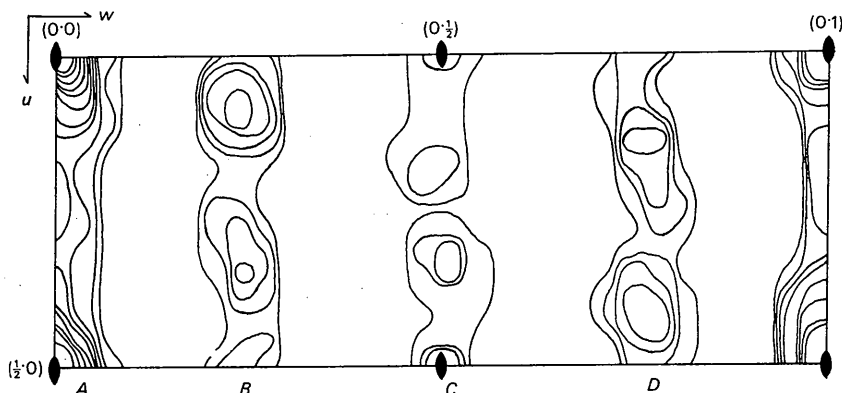


Fig. 1. Two-dimensional Patterson function, $P(u, w)$.

Table 2. Observed and calculated structure factors

M	K	L	F(OBS.)	F(CAL.)	M	K	L	F(OBS.)	F(CAL.)	M	K	L	F(OBS.)	F(CAL.)	M	K	L	F(OBS.)	F(CAL.)
0	0	0	46.27	56.18	1	3	-4	4.38	4.80	2	5	-9	4.31	4.15	4	0	-9	24.20	26.44
0	0	0	40.36	36.10	1	3	-4	5.20	5.95	2	5	-8	4.27	4.45	4	0	-9	26.34	30.09
0	0	0	26.28	26.57	1	3	-3	1.75	1.79	2	5	-7	2.81	2.65	4	0	-8	26.34	30.09
0	0	0	93.92	86.92	1	3	-2	3.81	3.81	2	5	-6	3.78	3.77	4	0	-7	51.35	48.15
0	0	0	46.80	38.32	1	3	-1	0.95	4.04	2	5	-5	4.37	3.72	4	0	-6	12.23	14.32
0	0	0	16.48	12.87	1	3	0	0.77	0.77	2	5	-4	4.03	3.77	4	0	-5	10.16	10.16
0	0	0	13.01	9.33	1	3	1	16.43	13.14	2	5	-3	0.21	0.21	4	0	-4	16.16	23.41
0	0	0	14.03	13.24	1	3	2	0.33	7.17	2	5	-2	0.94	0.25	4	0	-3	19.05	20.46
0	0	0	0.86	0.81	1	3	3	11.46	11.00	2	5	-1	8.91	5.27	4	0	-2	0.86	7.29
0	0	0	14.57	15.05	1	3	4	0.78	4.15	2	5	0	5.94	5.27	4	0	-1	9.31	6.04
0	0	0	15.60	15.54	1	3	5	11.57	11.09	2	5	1	7.33	6.04	4	0	0	7.48	6.21
0	0	0	13.94	14.72	1	3	6	4.63	4.25	2	5	2	4.85	11.67	4	0	10	14.15	11.53
0	0	0	15.60	13.56	1	3	7	11.57	10.81	2	5	3	10.04	3.70	4	0	11	10.17	9.16
0	0	0	11.94	11.90	1	3	8	0.68	0.56	2	5	4	0.78	5.41	4	0	12	4.13	2.98
0	0	0	9.67	9.78	1	3	9	11.57	10.94	2	5	5	4.14	10.38	4	0	13	10.02	2.98
0	0	0	9.62	9.57	1	3	10	4.78	4.70	2	5	6	5.02	5.40	4	0	14	9.05	10.20
0	0	0	11.94	11.90	1	3	11	0.68	0.56	2	5	7	0.91	3.88	4	0	15	7.87	7.96
0	0	0	9.67	9.78	1	3	12	11.57	10.94	2	5	8	4.14	10.38	4	0	16	4.13	2.98
0	0	0	9.62	9.57	1	3	13	4.78	4.70	2	5	9	5.02	5.40	4	0	17	9.05	10.20
0	0	0	11.94	11.90	1	3	14	0.68	0.56	2	5	10	0.91	3.88	4	0	18	7.87	7.96
0	0	0	9.67	9.78	1	3	15	11.57	10.94	2	5	11	4.14	10.38	4	0	19	4.13	2.98
0	0	0	9.62	9.57	1	3	16	4.78	4.70	2	5	12	5.02	5.40	4	0	20	9.05	10.20
0	0	0	11.94	11.90	1	3	17	0.68	0.56	2	5	13	0.91	3.88	4	0	21	7.87	7.96
0	0	0	9.67	9.78	1	3	18	11.57	10.94	2	5	14	4.14	10.38	4	0	22	4.13	2.98
0	0	0	9.62	9.57	1	3	19	4.78	4.70	2	5	15	5.02	5.40	4	0	23	9.05	10.20
0	0	0	11.94	11.90	1	3	20	0.68	0.56	2	5	16	0.91	3.88	4	0	24	7.87	7.96
0	0	0	9.67	9.78	1	3	21	11.57	10.94	2	5	17	4.14	10.38	4	0	25	4.13	2.98
0	0	0	9.62	9.57	1	3	22	4.78	4.70	2	5	18	5.02	5.40	4	0	26	9.05	10.20
0	0	0	11.94	11.90	1	3	23	0.68	0.56	2	5	19	0.91	3.88	4	0	27	7.87	7.96
0	0	0	9.67	9.78	1	3	24	11.57	10.94	2	5	20	4.14	10.38	4	0	28	4.13	2.98
0	0	0	9.62	9.57	1	3	25	4.78	4.70	2	5	21	5.02	5.40	4	0	29	9.05	10.20
0	0	0	11.94	11.90	1	3	26	0.68	0.56	2	5	22	0.91	3.88	4	0	30	7.87	7.96
0	0	0	9.67	9.78	1	3	27	11.57	10.94	2	5	23	4.14	10.38	4	0	31	4.13	2.98
0	0	0	9.62	9.57	1	3	28	4.78	4.70	2	5	24	5.02	5.40	4	0	32	9.05	10.20
0	0	0	11.94	11.90	1	3	29	0.68	0.56	2	5	25	0.91	3.88	4	0	33	7.87	7.96
0	0	0	9.67	9.78	1	3	30	11.57	10.94	2	5	26	4.14	10.38	4	0	34	4.13	2.98
0	0	0	9.62	9.57	1	3	31	4.78	4.70	2	5	27	5.02	5.40	4	0	35	9.05	10.20
0	0	0	11.94	11.90	1	3	32	0.68	0.56	2	5	28	0.91	3.88	4	0	36	7.87	7.96
0	0	0	9.67	9.78	1	3	33	11.57	10.94	2	5	29	4.14	10.38	4	0	37	4.13	2.98
0	0	0	9.62	9.57	1	3	34	4.78	4.70	2	5	30	5.02	5.40	4	0	38	9.05	10.20
0	0	0	11.94	11.90	1	3	35	0.68	0.56	2	5	31	0.91	3.88	4	0	39	7.87	7.96
0	0	0	9.67	9.78	1	3	36	11.57	10.94	2	5	32	4.14	10.38	4	0	40	4.13	2.98
0	0	0	9.62	9.57	1	3	37	4.78	4.70	2	5	33	5.02	5.40	4	0	41	9.05	10.20
0	0	0	11.94	11.90	1	3	38	0.68	0.56	2	5	34	0.91	3.88	4	0	42	7.87	7.96
0	0	0	9.67	9.78	1	3	39	11.57	10.94	2	5	35	4.14	10.38	4	0	43	4.13	2.98
0	0	0	9.62	9.57	1	3	40	4.78	4.70	2	5	36	5.02	5.40	4	0	44	9.05	10.20
0	0	0	11.94	11.90	1	3	41	0.68	0.56	2	5	37	0.91	3.88	4	0	45	7.87	7.96
0	0	0	9.67	9.78	1	3	42	11.57	10.94	2	5	38	4.14	10.38	4	0	46	4.13	2.98
0	0	0	9.62	9.57	1	3	43	4.78	4.70	2	5	39	5.02	5.40	4	0	47	9.05	10.20
0	0	0	11.94	11.90	1	3	44	0.68	0.56	2	5	40	0.91	3.88	4	0	48	7.87	7.96
0	0	0	9.67	9.78	1	3	45	11.57	10.94	2	5	41	4.14	10.38	4	0	49	4.13	2.98
0	0	0	9.62	9.57	1	3	46	4.78	4.70	2	5	42	5.02	5.40	4	0	50	9.05	10.20
0	0	0	11.94	11.90	1	3	47	0.68	0.56	2	5	43	0.91	3.88	4	0	51	7.87	7.96
0	0	0	9.67	9.78	1	3	48	11.57	10.94	2	5	44	4.14	10.38	4	0	52	4.13	2.98
0	0	0	9.62	9.57	1	3	49	4.78	4.70	2	5	45	5.02	5.40	4	0	53	9.05	10.20
0	0	0	11.94	11.90	1	3	50	0.68	0.56	2	5	46	0.91	3.88	4	0	54	7.87	7.96
0	0	0	9.67	9.78	1	3	51	11.57	10.94	2	5	47	4.14	10.38	4	0	55	4.13	2.98
0	0	0	9.62	9.57	1	3	52	4.78	4.70	2	5	48	5.02	5.40	4	0	56	9.05	10.20
0	0	0	11.94	11.90	1	3	53	0.68	0.56	2	5	49	0.91	3.88	4	0	57	7.87	7.96
0	0	0	9.67	9.78	1	3	54	11.57	10.94	2	5	50	4.14	10.38	4	0	58	4.13	2.98
0	0	0	9.62	9.57	1	3	55	4.78	4.70	2	5	51	5.02	5.40	4	0	59	9.05	10.20
0	0	0	11.94	11.90	1	3	56	0.68	0.56	2	5	52	0.91	3.88	4	0	60	7.87	7.96
0	0	0	9.67	9.78	1	3	57	11.57	10.94	2	5	53	4.14	10.38	4	0	61	4.13	2.98
0	0	0	9.62	9.57	1	3	58	4.78	4.70	2	5	54	5.02	5.40	4	0	62	9.05	10.20
0	0	0	11.94	11.90	1	3	59	0.68	0.56	2	5	55	0.91	3.88	4	0	63	7.87	7.96
0	0	0	9.67	9.78	1	3	60	11.57	10.94	2	5	56	4.14	10.38	4	0	64	4.13	2.98
0	0	0	9.62	9.57	1	3	61	4.78	4.70	2	5	57	5.02	5.40	4	0	65	9.05	10.20
0	0	0	11.94	11.90	1	3	62	0.68	0.56	2	5	58	0.91	3.88	4	0	66	7.87	7.96
0	0	0	9.67	9.78	1	3	63	11.57	10.94	2	5	59	4.14	10.38	4	0	67	4.13	2.98
0	0	0	9.62	9.57	1	3	64	4.78	4.70	2	5	60	5.02	5.40	4	0	68	9.05	10.20
0	0	0	11.94	11.90	1	3	65	0.68	0.56	2	5	61	0.91	3.88	4	0	69	7.87	7.96
0	0	0	9.67	9.78	1	3	66	11.57	10.94	2	5	62	4.14	10.38	4	0	70	4.13	2.98
0	0	0	9.62	9.57	1	3	67	4.78	4.70	2	5	63	5.02	5.40	4	0	71	9.05	10.20
0	0	0	11.94	11.90	1	3	68	0.68	0.56	2	5	64	0.91	3.88	4	0	72	7.87	7.96
0	0	0	9.67	9.78	1	3	69	11.57	10.94	2	5	65	4.14	10.38	4	0	73	4.13	2.98
0	0	0	9.62	9.57	1	3	70	4.78	4.70	2	5	66	5.02	5.40	4	0	74	9.05	10.20
0	0	0	11.94	11.90	1	3	71	0.68	0.56	2	5	67	0.91	3.88	4	0	75	7.87	7.96
0	0	0	9.67	9.78	1	3	72	11.57	10.94	2	5	68	4.14	10.38	4	0	76	4.13	2.98
0	0	0	9.62	9.57	1	3	73</												

Table 3. Bond lengths and angles of the valine molecules found in crystals

Bond lengths	L-Valine		DL-Valine	L-Valine.HCl		L-Valine. HCl.H ₂ O
	Molecule A	Molecule B				
C(1)-O(1)	1.245 ± 0.012 Å	1.276 ± 0.014 Å	1.248 ± 0.006 Å	1.200 ± 0.009 Å	1.229 ± 0.017 Å	1.27 Å
C(1)-O(2)	1.265 ± 0.016	1.243 ± 0.017	1.249 ± 0.006	1.309 ± 0.009	1.350 ± 0.017	1.30
C(1)-C(2)	1.518 ± 0.014	1.541 ± 0.014	1.527 ± 0.007	1.509 ± 0.009	1.501 ± 0.020	1.49
C(2)-C(3)	1.547 ± 0.015	1.516 ± 0.015	1.541 ± 0.007	1.558 ± 0.009	1.523 ± 0.020	1.54
C(3)-C(4)	1.534 ± 0.020	1.553 ± 0.017	1.516 ± 0.007	1.517 ± 0.009	1.503 ± 0.020	1.49
C(3)-C(5)	1.567 ± 0.017	1.525 ± 0.021	1.518 ± 0.007	1.532 ± 0.009	1.552 ± 0.020	1.58
C(2)-N(1)	1.496 ± 0.016	1.497 ± 0.016	1.483 ± 0.006	1.495 ± 0.009	1.490 ± 0.018	1.49
Bond angles						
O(1)-C(1)-O(2)	124.8 ± 1.0°	124.9 ± 1.1°	125.5 ± 0.4°	123.9 ± 0.6°	120.9 ± 1.5°	116°
O(1)-C(1)-C(2)	117.7 ± 0.9	116.0 ± 1.0	118.0 ± 0.4	123.7 ± 0.6	127.2 ± 1.5	123
O(2)-C(1)-C(2)	117.4 ± 1.0	119.1 ± 1.0	116.5 ± 0.4	112.4 ± 0.6	111.7 ± 1.5	121
C(1)-C(2)-N(1)	109.6 ± 0.9	109.2 ± 0.9	109.0 ± 0.4	106.2 ± 0.6	105.3 ± 1.5	108
C(1)-C(2)-C(3)	113.7 ± 0.9	109.3 ± 0.9	113.0 ± 0.4	114.5 ± 0.6	112.2 ± 1.5	110
N(1)-C(2)-C(3)	111.0 ± 0.9	110.3 ± 0.9	109.8 ± 0.4	109.8 ± 0.6	110.0 ± 1.5	114
C(2)-C(3)-C(4)	111.7 ± 1.0	110.2 ± 1.0	110.3 ± 0.4	110.3 ± 0.6	112.2 ± 1.5	112
C(2)-C(3)-C(5)	110.4 ± 0.9	111.6 ± 1.0	112.3 ± 0.4	111.8 ± 0.6	114.8 ± 1.5	111
C(4)-C(3)-C(5)	111.5 ± 1.0	109.3 ± 1.0	111.4 ± 0.4	113.0 ± 0.6	112.3 ± 1.5	110
State of rotation about						
C(2)-C(3)	<i>Gauche</i> I	<i>Trans</i>	<i>Gauche</i> I	<i>Gauche</i> I		<i>Gauche</i> II
Reference	(1)	(1)	(2)	(3)	(4)	(5)

(1) Present study. (2) Mallikarjunan & Thyagaraja Rao (1969). (3) Ando, Ashida, Sasada & Kakudo (1967). (4) Parthasarathy (1966). (5) Thyagaraja Rao (1968).

Haanappel, Potters, Loopstra, MacGillavry & Veenendaal (1955) were used for carbon, nitrogen and oxygen atoms.

Discussion of the structure

Molecular structure

The present crystal contains two crystallographically independent molecules *A* and *B* in the asymmetric unit. The bond lengths and angles for these two kinds of molecules are shown in Fig. 2 and listed in Table 3, together with their estimated standard deviations. The corresponding values obtained for the two kinds of molecules are very close to each other although they have different conformations. In Table 3, the dimensions of the valine molecules found in DL-valine, L-valine.HCl and L-valine.HCl.H₂O are listed for comparison. They are in agreement with each other except for those involved in the carboxyl groups. In the case of L-valine and DL-valine, the carboxyl groups are ionized and the molecules exist as a zwitterion, whereas in the case of the hydrohalide, the molecules take a cationic form. The dimensions of the carboxyl groups are, therefore, different to some extent in these two cases, as is usually found in amino acids.

In the present crystal, the carboxyl groups of the *A* and *B* molecules are coplanar with their respective C_α atoms within the limit of experimental error. However, as is clear from Table 4, the amino nitrogen atom deviates from the plane by 0.432 Å in *A* and 0.958 Å in *B*, which corresponds to the twisting of the C-N bond out of the plane of the carboxyl group by 19.5 and 43.7° respectively. These angles are the largest among those of the valine molecules found in various

crystals. In particular the latter angle is one of the largest found in various amino acids (Lakshminarayanan, Sasisekharan & Ramachandran, 1967). A similar tendency to twisting of the C-N bond is also found in the crystal of L-cysteine (Harding & Long, 1968).

Table 4. Perpendicular distances of the atoms from the least-squares plane through the carboxyl group and α-carbon atom

Molecule A	
O(1)	-0.005 Å
O(2)	-0.005
C(1)	0.013
C(2)	-0.004
N(1)	0.432
Molecule B	
O(11)	-0.003 Å
O(12)	-0.003
C(11)	0.009
C(12)	-0.002
N(11)	0.958

It is of especial interest to compare the side-chain conformations of the valine molecules in various crystals. All three possible rotational isomers of the valine molecule, *trans*, *gauche* I and *gauche* II in Fig. 3, have now been found to exist in the crystalline state. In the present crystal, molecules *A* and *B* take the *gauche* I and *trans* form respectively. The latter has never been found before in crystals. The internal rotation angles about the C_α-C_β bond are calculated for the valine molecules and are listed in Table 5. In L-cysteine, whose crystal structure markedly resembles that of L-valine,

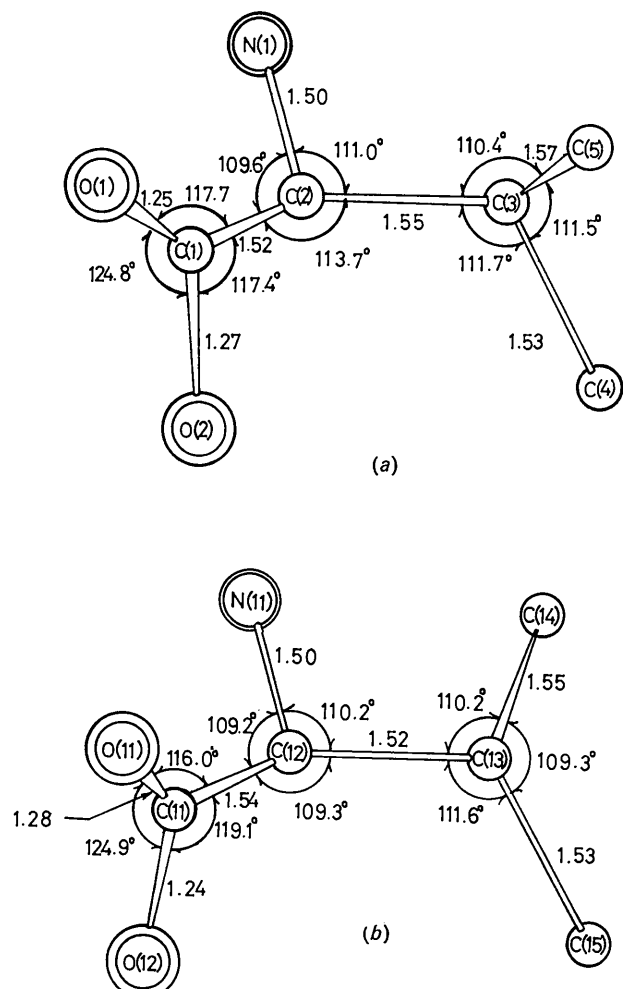


Fig. 2. Bond lengths (Å) and angles (°) of the L-valine molecules. (a) Molecule A, (b) molecule B.

the molecules are also found to take two different conformations, although the cysteine molecule has only one γ -atom.

The magnitudes and angles which define the principal axes of the ellipsoids of atomic thermal vibrations are given in Table 6, where α_{ij} are the angles between the j th principal axis ($j=1,2,3$) and the axes ($i=1,2,3$) fixed to the unit cell. A stereoscopic drawing of the crystal structure viewed along the c axis is shown in Fig. 7 in which the atoms are represented by ellipsoids of thermal vibration. This Figure was drawn by the plotter program *ORTEP* (Johnson, 1965). The area covered by the ellipsoids corresponds to a 50% probability of finding the centre of the atom in it.

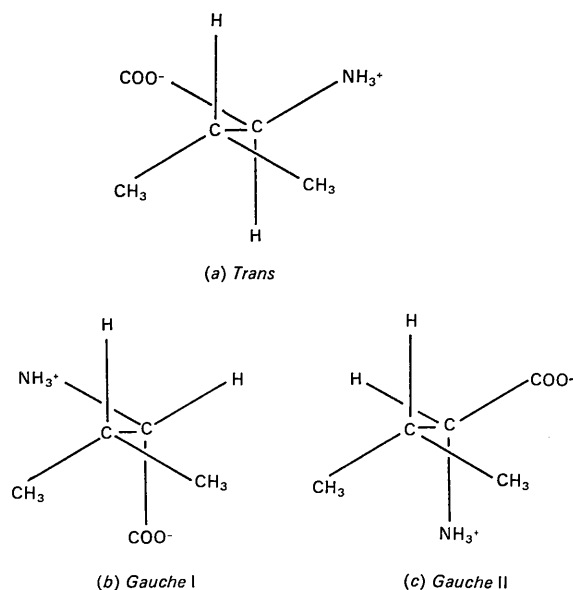


Fig. 3. Three possible rotational isomers of L-valine.

Table 5. Internal rotation angles of valine and cysteine molecules found in crystals

	ψ_2	χ_1	χ_{11}	χ_{12}	State of rotation about $C_\alpha-C_\beta$	Reference*
L-Valine						(1)
Molecule A	-19.5°		206.4°	81.8°	<i>Gauche I</i>	
Molecule B	-43.7		300.7	179.2	<i>Trans</i>	
L-Valine. HCl	-7.8		194.3	64.4	<i>Gauche I</i>	(2)
L-Valine. HBr	-11.6		195.5	74.0	<i>Gauche I</i>	(2)
L-Valine. HCl. H ₂ O	-3.7		53.9	289.0	<i>Gauche II</i>	(2)
DL-Valine	-21.0		209.0	82.0	<i>Gauche I</i>	(3)
L-Cysteine						(4)
First molecule	-3.0	72.6			S is <i>trans</i> to H $_\alpha$	
Second molecule	-36.1	189.9			S is <i>trans</i> to N	

In the case of crystalline L-valine the conformation angles, ψ_2 , χ_{11} and χ_{12} defined by Lakshminarayanan, Sasisekharan & Ramachandran (1967), are equivalent to the following internal rotation angles:

$$\begin{aligned}\psi_2 &= \tau[\text{O}(1)-\text{C}(1)-\text{C}(2)-\text{N}(1)] \\ \chi_{11} &= \tau[\text{N}(1)-\text{C}(2)-\text{C}(3)-\text{C}(4)] \\ \chi_{12} &= \tau[\text{N}(1)-\text{C}(2)-\text{C}(3)-\text{C}(5)]\end{aligned}$$

where, $\tau[A-B-C-D]$ is defined as the angle formed by the projection of the $A-B$ bond with that of $C-D$ when the projection is taken along the $B-C$ bond. The angle is taken as positive if the rotation to bring the projection of $A-B$ into that of $C-D$ coincides with that of the right-handed screw advancing along the $B-C$ bond.

* (1) Present study. (2) Lakshminarayanan, Sasisekharan & Ramachandran (1967). (3) Mallikarjunan & Thyagaraja Rao (1969). (4) Harding & Long (1968).

Table 6. *R.m.s. displacements and directions of principal axes of thermal vibration*

Molecule A	Principal axis	$U(j) \times 10^2$	$\cos \alpha_{1j}$	$\cos \alpha_{2j}$	$\cos \alpha_{3j}$
O(1)	1	15 Å	0.799	-0.596	-0.088
	2	17	0.601	0.783	0.161
	3	23	-0.028	-0.181	0.983
O(2)	1	15	-0.561	0.783	-0.270
	2	17	-0.745	-0.619	-0.246
	3	23	0.360	-0.063	-0.931
N(1)	1	15	-0.698	0.692	-0.186
	2	16	-0.532	-0.675	-0.511
	3	20	0.479	0.258	-0.839
C(1)	1	14	0.356	-0.833	0.423
	2	18	0.864	0.122	-0.489
	3	20	0.356	0.539	0.763
C(2)	1	13	0.518	0.855	-0.037
	2	16	0.852	-0.519	-0.070
	3	22	0.079	-0.005	0.997
C(3)	1	14	-0.687	-0.149	-0.711
	2	16	0.266	-0.962	-0.055
	3	22	0.676	0.227	-0.701
C(4)	1	14	-0.483	-0.713	-0.509
	2	24	-0.632	0.686	-0.360
	3	30	0.606	0.148	-0.782
C(5)	1	18	-0.440	-0.169	0.882
	2	22	-0.411	0.911	-0.030
	3	26	0.798	0.375	0.471
Molecule B					
O(11)	1	13	0.676	-0.728	-0.115
	2	19	0.736	0.676	0.048
	3	24	0.043	-0.117	0.992
O(12)	1	13	0.161	-0.968	0.192
	2	20	-0.899	-0.224	-0.376
	3	26	0.407	-0.112	-0.907
N(11)	1	14	-0.625	0.781	-0.025
	2	19	-0.701	-0.574	-0.423
	3	24	0.345	0.246	-0.906
C(11)	1	12	0.862	-0.486	-0.144
	2	17	0.475	0.874	-0.105
	3	23	0.177	0.022	0.984
C(12)	1	10	0.352	-0.909	0.222
	2	17	-0.908	-0.389	-0.156
	3	23	0.229	-0.147	-0.962
C(13)	1	15	0.508	-0.846	0.160
	2	19	0.806	0.533	0.258
	3	22	-0.303	-0.002	0.953
C(14)	1	13	0.508	-0.404	0.761
	2	25	-0.565	0.511	0.648
	3	28	0.650	0.759	-0.031
C(15)	1	18	0.584	-0.646	-0.491
	2	22	-0.232	0.447	-0.864
	3	31	-0.778	-0.619	-0.111

The r.m.s. displacement $U(j)$ is directed along the j th axes of the ellipsoid where α_{1j} , α_{2j} and α_{3j} are the angles between j th axis and the a , b and c^* axes respectively.

Table 7. *Intermolecular short N...O distances and C-N...O angles*

N(1)...O	N(1)...O(2) [I(010)]	N(1)...O(11) [I(010)]	N(1)...O(11) [II(000)]	N(1)...O(12) [II(010)]
C(2)—N(1)...O	2.870 ± 0.013 Å	2.795 ± 0.011	2.859 ± 0.013	3.194 ± 0.013
	115.5 ± 0.6°	109.1 ± 0.6	86.2 ± 0.6	145.3 ± 0.7
N(11)...O	N(11)...O(12) [I(010)]	N(11)...O(1) [II(0T0)]	N(11)...O(2) [I(T00)]	N(11)...O(1) [I(T00)]
C(12)—N(11)...O	2.881 ± 0.014 Å	2.780 ± 0.013	2.917 ± 0.011	3.068 ± 0.011
	114.4 ± 0.7°	111.2 ± 0.7	106.4 ± 0.7	145.8 ± 0.7

The numbers I and II denote the operations,

$$\begin{aligned} \text{I: } & x, y, z \\ \text{II: } & 1-x, \frac{1}{2}+y, 1-z, \end{aligned}$$

where the values of x , y and z are given in Table 1.

Translations along the three edges of the unit cell are given in parentheses.

Hydrogen bonds

In Table 7 short intermolecular N...O distances and C-N...O angles are listed. In each molecule the nitrogen atom is surrounded by four oxygen atoms at short distances. The arrangement of these oxygen atoms

is shown in Fig. 4 in stereographic projection in which the direction of the C(2)-N(1) or C(12)-N(11) bond is taken as the polar axis and the suggested N-H directions are indicated. It may be seen that in molecule *A* the two oxygen atoms O(11) [I (010)] and O(2) [I (010)]

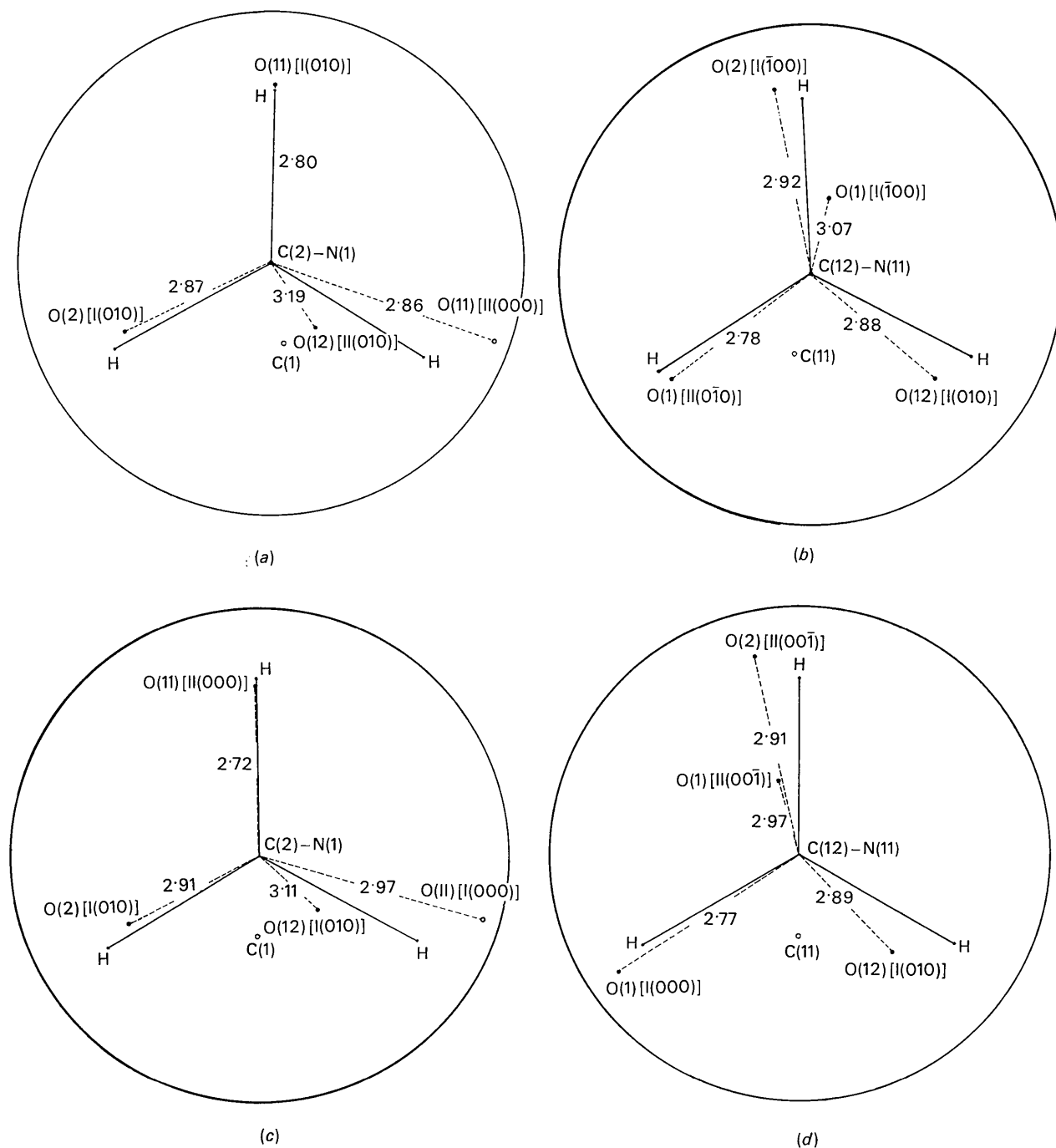


Fig. 4. Stereographic projections showing the arrangement of oxygen atoms around the amino nitrogen atom. Notations of the symmetry operations are shown in Table 7. The direction of the C-N bond is taken as the polar axis and suggested N-H directions are indicated. L-valine: (a) molecule *A*, (b) molecule *B*; L-cysteine (Harding & Long, 1968): (c) first molecule, (d) second molecule.

are situated in approximately tetrahedral directions and the two amino hydrogen atoms will lie respectively nearly on the lines joining the amino nitrogen atom and the two oxygen atoms. The third amino hydrogen atom seems to be on a line nearly bisecting the angle $O(11) [II (000)]-N(1)-O(12) [II (010)]$ and forms a bifurcated hydrogen bond. In molecule *B*, on the other hand, three oxygen atoms, $O(1) [II (0\bar{1}0)]$, $O(12) [I (010)]$ and $O(2) [I (\bar{1}00)]$ are situated in approximately tetrahedral directions, with a maximum deviation of about 15° from the tetrahedral angle and it seems that these three oxygen atoms take part in hydrogen bonds. The fourth oxygen atom $O(1) [I (\bar{1}00)]$ is linked mainly by electrostatic forces to the NH_3^+ group. A similar arrangement has been suggested for L-valine.HCl (Ando, Ashida, Sasada & Kakudo, 1967).

Crystal structure

The projection of the crystal structure of L-valine along the *b* axis is shown in Fig. 5. It is seen that the structure is made up of double layers of molecules extending parallel to the (001) plane. Within the layers,

the molecules are held together through the $N-H \cdots O$ hydrogen bonds mentioned above. Two of these hydrogen bonds for each molecule, $N(1) \cdots O(2) [I (010)]$ and $N(1) \cdots O(11) [I (010)]$ for molecule *A* and $N(11) \cdots O(12) [I (010)]$ and $N(11) \cdots O(2) [I (\bar{1}00)]$ for molecule *B*, link the molecules to form a single layer. The structure of the single layer is shown in Figs. 6 and 7. Other hydrogen bonds, $N(1) \cdots O(11) [II (000)]$ and $N(1) \cdots O(12) [II (010)]$ for molecule *A*, which presumably form a bifurcated hydrogen bond, and $N(11) \cdots O(1) [II (0\bar{1}0)]$ for molecule *B*, join the single layers to form a double layer. The double layers are stacked along the *c* axis but they are separated from each other by hydrocarbon side-chains.

The arrangement of the side-chains within the single layer is best illustrated in Fig. 7. This Figure is a stereoscopic view of the crystal structure, viewed along a direction from the hydrophobic region between the double layers down to the hydrophilic region. As this direction is nearly parallel to the $C_\alpha-C_\beta$ bonds, the Figure clearly illustrates how the C_γ atoms are packed together closely enough within the layer. It is seen that

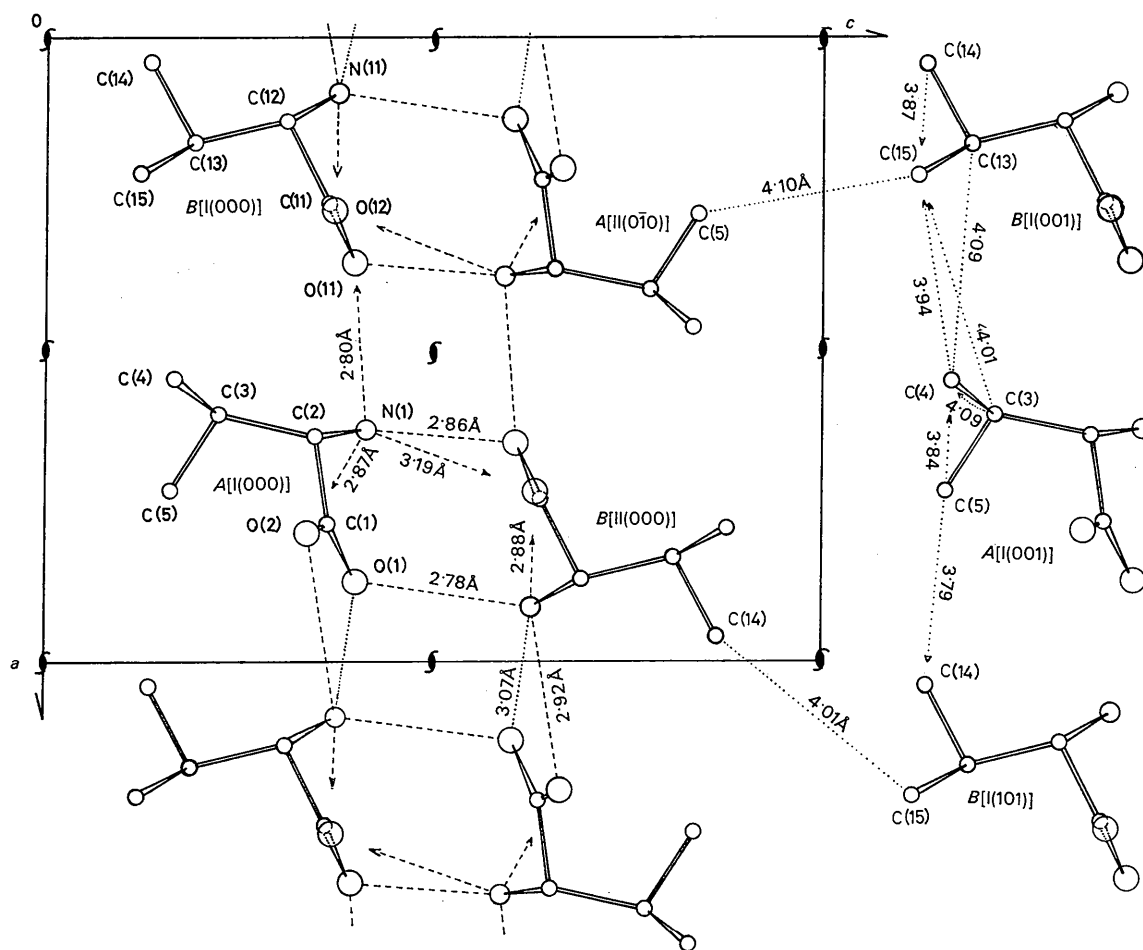


Fig. 5. Projection of the crystal structure along the *b* axis. Hydrogen bonds are shown by broken lines and the closest approaches of the side-chain atoms are also shown.

the *B* molecules are situated nearly at the centre of the lattice formed by the *A* molecules, and the backbones of the *A* and *B* molecules, consisting of the carboxyl and amino groups, are arranged nearly parallel to each other, whereas the side-chains do not adopt such an arrangement.

Of especial interest is that the side-chains are packed together in a manner resembling that of the $O\perp$ packing of long chain hydrocarbons (Bunn, 1939). This is one of the most stable forms of carbon chain packing, and it seems that this side-chain packing scheme in the L-valine molecules in the present crystal gives rise to the different conformations of the *A* and *B* molecules about the $C_\alpha-C_\beta$ bonds.

In Table 8 the intermolecular short contacts less than 4.2 Å are listed. They are nearly of the same order of magnitude as those found in the usual hydrocarbon chain packing. There are no unusually close contacts between the methyl or methine carbon atoms.

Table 8. Packing distances shorter than 4.2 Å between side-chain carbon atoms

Within the single layer

C(3) [I(000)]...C(15) [I(010)]	4.01 ± 0.02 Å
C(13) [I(000)]...C(4) [I(000)]	4.09
C(3) [I(000)]...C(4) [I(010)]	4.09
C(14) [I(000)]...C(15) [I(010)]	3.87

Table 8 (cont.)

C(4) [I(000)]...C(15) [I(010)]	3.94
C(5) [I(000)]...C(4) [I(010)]	3.84
C(5) [I(000)]...C(14) [I(110)]	3.79

Between the double layers

C(5) [I(000)]...C(15) [II(00I)]	4.10
C(14) [I(000)]...C(15) [II(10I)]	4.01

The symmetry operation notation is as in Table 7.

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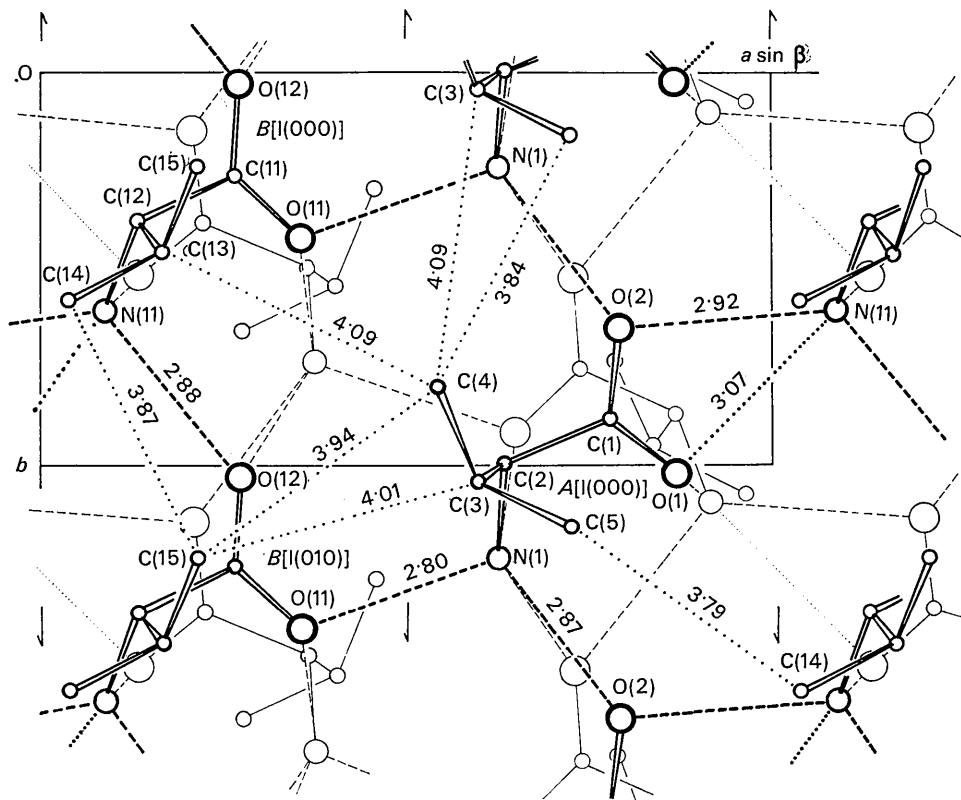


Fig. 6. Projection of the crystal structure along the *c* axis showing the structure of the single layer. Hydrogen bonds are shown by broken lines and the closest approaches of the side-chain atoms within the single layer are also shown.

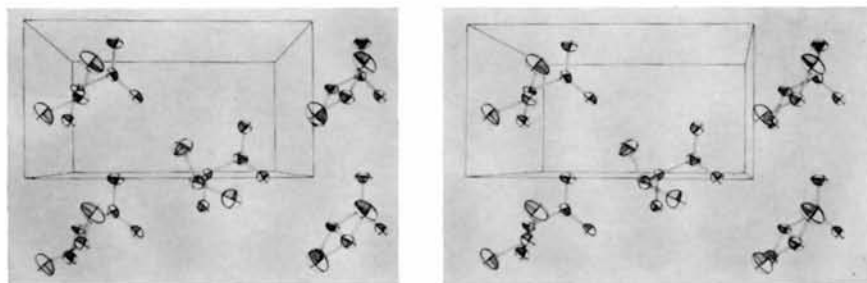


Fig. 7. Stereoscopic drawing of the single layer of the L-valine crystal viewed along the b axis. The probability of finding the centre of the atom in the ellipsoid is 50%.

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The Crystal and Molecular Structure of the *cis-syn* Photodimer of Uracil

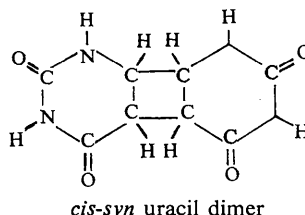
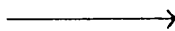
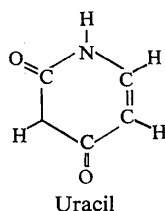
BY ELINOR ADMAN AND LYLE H. JENSEN

Department of Biological Structure, University of Washington, Seattle, Washington, U.S.A.

(Received 25 July 1969)

The *cis-syn* photodimer ($C_8H_8N_4O_4$) of uracil, formed upon ultraviolet irradiation of the monomer in frozen aqueous solution, crystallizes in the monoclinic system with cell dimensions $a = 13.249 \pm 0.001$, $b = 11.191 \pm 0.001$, $c = 6.279 \pm 0.0003$ Å, $\beta = 94.751 \pm 0.004^\circ$, space group $P2_1/n$. The molecules exhibit a non-planar cyclobutane ring and non-planar heterocyclic rings, with bond lengths and angles characteristic of each portion. All possible hydrogen bonds are formed, holding the molecules together in an extensive three-dimensional network.

Irradiation of pyrimidines and their derivatives with ultraviolet light under various conditions produces dimers with a cyclobutane linkage formed by joining the monomers at the 5-6 double bond, *i.e.*



Uracil, thymine, and mixed uracil-thymine dimers have been isolated from irradiated deoxyribonucleic acid

(DNA) *in vitro* (Setlow & Carrier, 1966) and, along with other photoproducts, are involved in the loss of activity of DNA. Uracil dimers have also been isolated from TMV-RNA (tobacco mosaic virus ribonucleic

acid), but their role is less well defined (Merriam & Gordon, 1967).

Table 1. *Examples of pyrimidine photodimers with known structures*

Isomer	Monomer	Source	Method of identification*	References
I <i>cis-syn</i>	Uracil	Frozen aqueous solution	Chemical degrad. XRD	Dönges & Fahr (1966) This work
	Thymine	Frozen aqueous solution	Chemical degrad. XRD	Blackburn & Davies (1967) Kuneida & Witkop (1967) Wei & Einstein (1968)
III <i>cis-anti</i>	Dimethylthymine	<i>E. coli</i> DNA	Chemical degrad.	Blackburn & Davies (1967)
	Dimethylthymine	Frozen aqueous solution Frozen aqueous solution	XRD XRD	Camerman & Camerman (1968) Camerman, Weinblum & Nyburg (1969)
IV <i>trans-anti</i>	Thymine	Frozen aqueous solution of thymidine	XRD	Camerman & Nyburg (1969)
	1-methylthymine	Frozen aqueous solution	XRD	Einstein, Hosszu, Longworth, Rahn & Wei (1967)

* XRD, X-ray diffraction.