BULLETIN OF THE CHEMICAL SOCIETY OF JAPAN VOL. 40 476—487 (1967)

The Crystal Structure and the Absolute Configuration of (+)-2-Benzylglutamic Acid Hydrobromide Dihydrate*[1]

Tamaichi Ashida, Yoshio Sasada*[2] and Masao Kakudo

Institute for Protein Research, Osaka University, Joancho, Kita-ku, Osaka

(Received August 11, 1966)

The crystal structure of (+)-2-benzylglutamic acid hydrobromide dihydrate has been determined using three-dimensional X-ray intensity data. The crystal is orthorhombic, with four formula units in a unit cell with the dimensions: $a=8.38$, $b=10.54$, and $c=17.68$ Å, the space group being $P2_12_12_1$. The structure was solved by the heavy atom method, and its parameters were refined by the least-squares method using anisotropic thermal parameters, the final R being 0.073. The absolute configuration of the glutamic acid has also been determined to be D-(+)-2-benzylglutamic acid, $[\alpha]_D^{20}$ +1.65° (*c* 10, 4 N HCl). The conformation of the carbon skeleton of the glutamic acid is different from any of the glutamic acids so far analyzed, due to the internal rotations of the C–C bonds. A detailed comparison of the conformations of several glutamic acids and glutamines will be given. Nine independent hydrogen bonds make a rather unique and complicated three-dimensional network. Among these, two between the carboxyl groups (donor) and the water molecules (acceptor) are found to be fairly strong, their bond lengths being 2.55 and 2.51 Å.

Recently, Izumi and his collaborators[1-4] have extensively investigated the asymmetric hydrogenation of methyl acetoacetate to methyl 3-hydroxybutyrate. They have used Raney nickel catalysts, modified under various conditions, with several optically active compounds, such as amino acids and hydroxy acids. α-*C*-substituted glutamic acids, such as 2-methyl- and 2-benzylglutamic acid, were also tested as the modifying reagents; the natures of the activities of the catalysts modified by them have been found to be quite different from that of the catalyst with L-glutamic acid.[4] Thus, levorotatory methyl 3-hydroxybutyrate is obtained by the catalyst modified with (+)-2-methylglutamic acid, and the dextrotatory product with (+)-2-benzylglutamic acid; while by the catalyst modified with L-glutamic acid, the direction of the optical rotation of the product is much influenced by the pH and by the temperature of the modifying solution. The determination of the absolute configuration of such α-*C*-substituted glutamic acids as well as their steric conformations are necessary in order to study the mechanism of such asymmetric reactions. DL-2-Benzylglutamic acid was newly synthesized, and its optical resolution was performed by Izumi and his collaborators.[5] The optical rotation of (+)-2-benzylglutamic acid was $[\alpha]_D^{20}$ +1.65° (*c* 10, 4 N HCl).

2-Benzylglutamic acid is characterized by the lack of a hydrogen atom on the asymmetric α-carbon atom. Though the crystal structures of many amino acids have been studied, the structural analyses of α-*C*-dialkyl glycines have been rather few; the only example is α-aminoisobutyric acid.[6] The substituted groups, a propionic acid residue and a benzyl group, in 2-benzylglutamic acid are, however, quite a bit larger than the two methyl groups in α-aminoisobutyric acid; thus the crowded surroundings of the α-carbon atom in 2-benzylglutamic acid are rather interesting from the viewpoint of structural chemistry. The crystal structures of β-glutamic acid,[7] glutamic acid hydrochloride,[8] glutamine[9] and glutathione[10] have already been reported; the effect of the substitution of a large group on the conformation of glutamic acid will also be clarified by the structure analysis of the present compound. On the other hand, the present amino acid is phenylalanine with a propionic acid residue substituted at the α-carbon atom. Phenylalanine is a rare example of a substance the crystal structure of which has not

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*[1] Presented at the 19th Annual Meeting of the Chemical Society of Japan, Yokohama, March, 1966.

*[2] Present address: Faculty of Science, Tokyo Institute of Technology, Ookayama, Meguro-ku, Tokyo.

1) Y. Izumi, M. Imaida, H. Fukawa and S. Akabori, This Bulletin, **36**, 21 (1963).

2) Y. Izumi, M. Imaida, H. Fukawa and S. Akabori, *ibid.*, **36**, 155 (1963).

3) S. Tatsumi, M. Imaida, Y. Fukuda, Y. Izumi and S. Akabori, *ibid.*, **37**, 846 (1964).

4) Y. Izumi, S. Tatsumi, M. Imaida, Y. Fukuda and S. Akabori, *ibid.*, **38**, 1206 (1965).

5) Y. Izumi, S. Tatsumi, M. Imaida, Y. Fukuda and S. Akabori, *ibid.*, **38**, 1338 (1965).

6) S. Hirokawa, S. Kuribayashi and I. Nitta, *ibid.*, **25**, 192 (1952).

7) S. Hirokawa, *Acta Cryst.*, **8**, 637 (1955).

8) B. Dawson, *ibid.*, **6**, 81 (1953).

9) W. Cochran and B. R. Penfold, *ibid.*, **5**, 644 (1952).

10) W. B. Wright, *ibid.*, **11**, 632 (1958).

yet been reported, though one peptide, glycylphenylalanyl-glycine,[11] has been reported on.

The present paper will deal with the crystal structure of (+)-2-benzylglutamic acid hydrobromide dihydrate as determined and refined by three-dimensional X-ray analysis. The absolute configuration of the amino acid will also be determined using the anomalous dispersion effect of the bromine atom.

Experimental

The crystals of (+)-2-benzylglutamic acid hydrobromide were obtained from its aqueous solution as rods elongated along the a axis. They were kindly supplied by Professor Yoshiharu Izumi of this Institute. The unit cell dimensions were obtained from Weissenberg photographs about the principal axes. The powder-diffraction patterns of aluminum were superimposed on the photographs as a standard. The dimensions are:

$a=8.28\pm0.02$, $b=10.54\pm0.02$, and $c=17.68\pm0.02$ Å.

From the systematic absences of $h00$, $0k0$ and $00l$ for h, k and l odd, the space group was found to be $P2_12_12_1$. The density of the crystal, as measured by the flotation method, was 1.515 g cm^{-3}, whereas the calculated value was 1.37 gcm^{-3} on the basis of four formula units per cell. A good agreement between the observed and the calculated values was obtained by assuming two crystallization water molecules per asymmetric unit; the calculated value thus became 1.525 g cm^{-3}. The presence of the crystallization water was later confirmed by the chemical analysis; thus the crystal was found to be (+)-2-benzylglutamic acid hydrobromide dihydrate.

Three-dimensional intensity data were collected from the equi-inclination Weissenberg photographs, using Cu$K\alpha$ radiation The crystals were rotated around the a axis (h=0 to 6) and the b axis (k=0 to 4). Intensities were measured visually by comparison with a standard scale; they ranged from 1 to 15000 on an arbitrary scale. A total of 1786 reflections were obtained, of which 107 were too weak to be estimated. They were corrected for Lorentz and polarization factors, and the spot-shape correction given by Phillips[12] was applied to the elongated spots No absorption corrections were made, though they seemed necessary because of the large linear absorption coefficient for Cu$K\alpha$ radiation, μ=42.2 cm^{-1}; the cross sections of the crystals used in the experiments were both about 0.015 × 0.01 cm.

Structure Determination

The coordinates of the bromide ion were determined from the Patterson function projected on the a and b axes. The three-dimensional electron-density function was then synthesized, using all the observed reflections with phases assigned by the bromide ion. Though there appeared several false peaks of heights comparable with those of carbon atoms, a set of coordinates of all the atoms, including two water molecules, was established without difficulty. Using the coordinates of all the non-hydrogen atoms thus obtained, the structure factors were then calculated for all the observed reflections; the error index, $R=\sum|F_o-F_c|/\sum F_o$, was 0.23. In the second three-dimensional electron-density map the structure showed up clearly.

The structure was subjected to least-squares refinement using the block-diagonal matrix approximation. In the first step all the atoms were treated as isotropic; after two cycles the error index decreased from 0.20 to 0.14. Then all the non-hydrogen atoms were assigned with anisotropic thermal parameters; the reflections used in the refinement were those with $\sin\theta/\lambda$ values of less than 0.55 (1237 reflections). After several cycles,

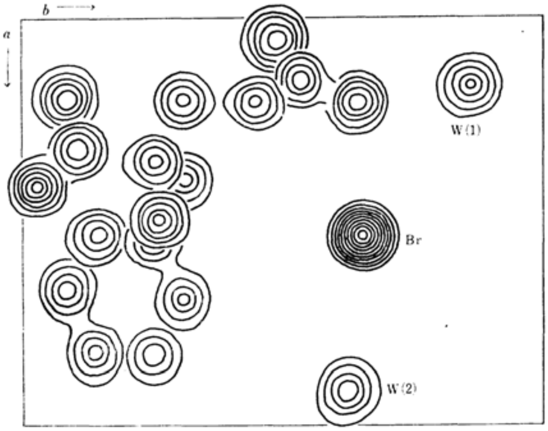

Fig. 1. A composite drawing of the final electron-density map, viewed along the c axis. Contours are at intervals of 2 e. Å^{-3}, beginning with the 2 e. Å^{-3} contour. For Br, contours are at intervals of 6 e. Å^{-3} beginning with 6 e. Å^{-3}.

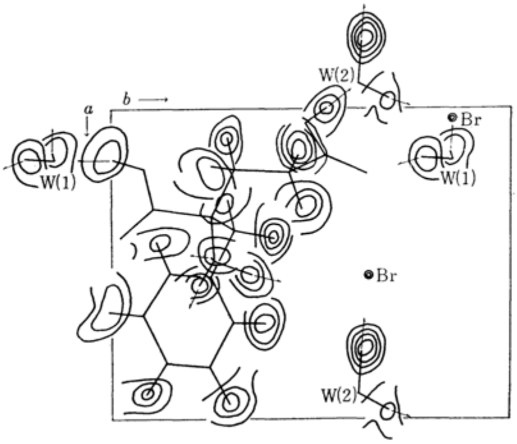

Fig. 2. A composite drawing of the final difference map, viewed along the c axis. The contributions of the hydrogen atoms were omitted from the structure factor calculations. Contours are at intervals of 0.15 e.Å^{-3}, beginning with the 0.15 e. Å^{-3} contour.

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[11] R. E. Marsh and J. P. Glusker, *ibid.*, **14**, 1110 (1961).

[12] D. C. Phillips, *ibid.*, **9**, 819 (1956).

R decreased to 0.079. At this stage, the difference Fourier function was synthesized using these 1237 reflections. Several residual peaks with heights of from 0.3 to 0.7 e.Å^{-3} appeared, and most of them were found at the sites where hydrogen atoms were expected to be present. Finally, all the hydrogen atoms with isotropic temperature factors were included in the refinement; the error

TABLE 1.

(a) Atomic coordinates (in fraction of cell edges) and their standard deviations in 10^{-3} Å

Atom	x	$\sigma(x)$	y	$\sigma(y)$	z	$\sigma(z)$
Br	0.5337	1	0.6500	1	0.0522	1
O(1)	0.1964	7	0.0839	6	0.1724	7
O(2)	0.4133	7	0.0278	6	0.2388	6
O(3)	0.0447	8	0.4867	6	0.1679	7
O(4)	0.2032	7	0.6425	7	0.2078	7
W(1)	0.1660	9	0.8610	7	0.1245	7
W(2)	0.9212	8	0.6229	9	0.0638	8
N	0.4945	8	0.2635	7	0.2760	7
C(1)	0.3226	10	0.1056	8	0.2128	8
C(2)	0.3504	10	0.2506	8	0.2243	8
C(3)	0.1997	10	0.3058	9	0.2628	9
C(4)	0.2048	11	0.4478	9	0.2785	9
C(5)	0.1502	10	0.5338	9	0.2139	9
C(6)	0.3946	10	0.3082	9	0.1459	9
C(7)	0.5441	11	0.2500	8	0.1105	7
C(8)	0.6924	11	0.3051	9	0.1232	10
C(9)	0.8329	12	0.2481	11	0.0926	9
C(10)	0.8218	11	0.1356	10	0.0512	9
C(11)	0.6702	12	0.0809	10	0.0385	9
C(12)	0.5321	11	0.1394	10	0.0675	7

(b) Temperature factors in form of

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

Atom	β_{11}	β_{22}	β_{33}	β_{12}	β_{13}	β_{23}
Br	0.0208	0.0108	0.0023	0.0018	0.0003	−0.0011
O(1)	0.0130	0.0047	0.0032	−0.0011	−0.0049	−0.0001
O(2)	0.0142	0.0035	0.0028	0.0024	−0.0019	−0.0003
O(3)	0.0166	0.0056	0.0036	−0.0035	−0.0083	0.0009
O(4)	0.0147	0.0038	0.0034	−0.0024	−0.0032	0.0015
W(1)	0.0288	0.0043	0.0029	−0.0039	−0.0043	0.0000
W(2)	0.0176	0.0131	0.0044	−0.0004	−0.0058	0.0033
N	0.0098	0.0045	0.0021	−0.0004	−0.0022	0.0009
C(1)	0.0109	0.0033	0.0020	−0.0016	0.0011	0.0003
C(2)	0.0109	0.0034	0.0018	0.0015	0.0006	0.0008
C(3)	0.0111	0.0049	0.0018	−0.0005	0.0017	0.0002
C(4)	0.0121	0.0050	0.0022	0.0013	−0.0000	0.0008
C(5)	0.0105	0.0050	0.0027	0.0012	0.0001	−0.0015
C(6)	0.0125	0.0052	0.0019	0.0013	−0.0004	0.0030
C(7)	0.0135	0.0046	0.0013	−0.0012	−0.0004	0.0007
C(8)	0.0132	0.0053	0.0027	−0.0020	0.0024	0.0006
C(9)	0.0152	0.0074	0.0024	−0.0029	0.0023	−0.0010
C(10)	0.0153	0.0077	0.0020	−0.0011	0.0018	0.0016
C(11)	0.0208	0.0074	0.0022	−0.0005	0.0026	−0.0016
C(12)	0.0129	0.0073	0.0018	−0.0013	−0.0012	0.0002

(c) Atomic coordinates and isotropic temperature factors for the hydrogen atoms

Atom	x	y	z	B
H(1)	0.161	0.002	0.162	3.8
H(2)	0.000	0.541	0.129	3.9
H(3)	0.154	0.776	0.145	5.2
H(4)	0.137	0.857	0.078	5.0
H(5)	0.801	0.634	0.059	4.5
H(6)	0.965	0.701	0.033	5.9
H(7)	0.533	0.358	0.274	2.9
H(8)	0.560	0.227	0.257	3.8
H(9)	0.484	0.249	0.328	3.2
H(10)	0.099	0.289	0.236	1.9
H(11)	0.190	0.252	0.316	3.1
H(12)	0.147	0.466	0.324	2.6
H(13)	0.327	0.481	0.296	2.9
H(14)	0.295	0.292	0.106	2.8
H(15)	0.417	0.410	0.154	2.3
H(16)	0.697	0.392	0.158	2.3
H(17)	0.950	0.293	0.098	2.6
H(18)	0.925	0.089	0.028	4.1
H(19)	0.662	0.995	0.003	2.0
H(20)	0.432	0.107	0.059	4.3

Table 2. Observed and calculated structure factors

(×5)

L	FO	FC
H,K=	0	0
2	192	158
4	255	264
6	487	508
8	379	399
10	453	466
12	325	330
14	27	26
16	53	56
18	276	265
20	73	73
22	69	66
H,K=	1	0
1	305	302
2	20	16
3	287	285
4	676	752
5	632	690
6	103	97
7	94	102
8	87	87
9	209	193
10	55	52
11	118	112
12	25	34
13	279	271
14	79	69
15	202	186
16	90	90
17	131	123
18•	0	3
19•	0	6
20	27	32
21	64	62
22	36	42
H,K=	2	0
0	295	323
1	224	238
2	545	561
3	39	44
4	64	61
5•	9	9
6	220	218
7	122	113
8	336	315
9	177	165
10	378	380
11	29	25
12	61	64
13	195	192
14	26	30
15	48	53
16	111	116
17	55	56
18	133	132
19	62	61
20	94	94
21	22	30
22	26	20
H,K=	3	0
1	443	456
2	160	167
3	288	277
4	463	438
5	446	438
6	241	239
7	114	115
8	62	62
9	39	42
10	147	141
11	99	94
12•	11	2
13	189	180
14	209	200
15	138	143
16	48	54
17	87	86
18	36	35
19	25	28
20	68	71
21	43	48
H,K=	4	0
0	166	176
1	187	183
2	160	156
3	200	189
4	60	63
5	43	42
6	44	44
7	248	235
8	216	210
9	154	155
10	113	113
11	128	120
12	76	79
13•	0	0
14	36	37
15	20	22
16	62	58
17	86	77
18	101	97
19	106	103
20	27	28
H,K=	5	0
1	121	115
2	206	199
3	235	230
4	196	200
5	142	144
6	242	222
7	71	70
8	26	22
9•	0	8
10	51	53
11•	15	3
12	154	147
13	115	115
14	150	147
15	34	42
16	62	57
17	30	27
18•	16	9
19	25	20
H,K=	6	0
0	240	229
1	266	262
2	27	17
3	23	20
4	55	51
5	32	29
6	46	42
7	54	53
8	62	60
9	181	181
10	26	27
11	66	64
12	100	102
13	61	55
14•	0	2
15	36	22
16	22	21
17	64	66
18	51	54
H,K=	7	0
1	72	77
2	128	120
3	36	44
4	244	227
5	60	63
6	87	84
7	43	46
8	60	57
9•	0	2
10•	12	17
11•	19	26
12	100	89
13•	13	18
14	83	76
15	20	27
16	82	64
H,K=	8	0
0	127	126
1	118	127
2•	0	0
3	33	35
4•	0	5
5•	12	6
6	25	15
7	73	65
8	26	24
9	86	66
10•	0	13
11	90	77
12•	0	15
13•	11	6
14•	18	21
H,K=	9	0
1•	0	2
2	36	37
3•	0	1
4	50	42
5	33	30
6	41	36
7•	0	7
8	33	29
9•	0	10
10	27	25
11•	15	20
H,K=	10	0
0•	13	12
1	62	50
2	57	49
3•	11	15
4•	11	11
5•	0	1
6•	8	4
7	55	53
H,K=	0	1
1	167	159
2	135	146
3	315	316
4	240	251
5	217	226
6	120	117
7	358	372
8	171	166
9	234	231
10	150	152
11	287	296
12	80	87
13	58	65
14	166	165
15	68	71
16	26	26
17	117	119
18	64	67
19	83	76
20	50	48
21	73	69
22	46	48
H,K=	1	1
0	25	21
1	157	182
2	78	73
3	378	391
4	381	385
5	207	225
6	401	417
7	106	105
8	181	170
9	196	194
10	94	105
11	213	208
12	135	131
13	117	118
14	145	142
15	44	47
16	168	164
17	72	71
18	61	66
19	78	76
20•	0	7
21	64	65
22	50	49
H,K=	2	1
0	323	355
1	453	500
2	365	389
3	360	380
4	159	155
5	260	258
6	276	258
7	231	226
8	240	234
9	298	300
10	101	96
11	241	224
12	160	158
13	94	96
14	124	123
15•	0	10
16	143	141
17	108	99
18	57	54
19	100	97
20	57	56
21	71	66
22	43	50
H,K=	3	1
0	191	215
1	122	144
2	294	299
3	325	326
4	241	240
5	212	203
6	435	422
7	291	274
8	58	60
9	53	54
10	252	234
11	166	153
12	231	223
13	171	166
14	103	105
15	65	68
16	97	100
17	25	43
18	37	36
19	87	81
20	39	37
21	32	34
H,K=	4	1
0	65	63
1	175	165
2	125	135
3	133	140
4	174	126
5	139	125
6	113	108
7	237	214
8	111	111
9	108	105
10	223	213
11	200	203
12	34	32
13	44	56
14	96	94
15	121	119
16	82	84
17	36	39
18	34	26
19	55	51
20	39	37
H,K=	5	1
0	118	129
1	104	118
2	143	154
3	219	225
4	157	170
5	173	171
6	140	138
7	154	145
8	138	131
9	79	73
10	139	130
11	100	92
12	110	109
13	87	91
14•	0	15
15	93	93
16	33	40
17	85	80
18	50	46
19	22	25
H,K=	6	1
0	46	37
1	80	88
2	142	143
3	48	50
4	83	77
5	99	91
6	40	32
7	68	68
8	163	155
9	25	22
10	73	63
11	55	57
12	82	79
13	65	66
14•	0	4
15	30	28
16	22	22
17	36	39
18	26	26
H,K=	7	1
0	27	29
1	27	12
2	69	71
3	27	31
4•	18	27
5	113	113
6•	18	29
7	107	98
8	65	53
9	27	28
10	36	35
11	32	33
12	47	50
13	50	41
14•	0	6
15	46	39
16•	16	20
H,K=	8	1
0	106	101
1	25	24
2	27	31
3	62	60
4	58	50
5	20	14
6	66	59
7	72	64
8	54	49
9•	18	22
10	58	50
11•	16	23
12	37	32
13	39	31
14•	11	8
H,K=	9	1
0•	15	6
1•	15	4
2	44	40
3	36	37
4	26	26
5	50	41
6•	0	13
7	36	32
8	33	27
9•	18	12
10	37	39
H,K=	10	1
0•	19	15
1•	13	10
2•	19	22
3	26	22
4•	18	18
5•	18	17
6	29	28
H,K=	0	2
0	311	360
1	318	344
2	256	240
3	519	523
4	189	170
5	907	929
6	360	326
7	690	659
8	87	77
9	143	136
10	29	25
11	195	185
12	146	136
13	302	285
14•	15	15
15	206	205
16•	19	23
17	135	135
18	47	48
19•	12	3
20	27	34
21	82	83
22	25	32
H,K=	1	2
0	498	502
1	460	469
2	429	426
3	438	421
4	174	155
5	376	358
6	259	241
7	224	185
8	269	248
9	256	230
10	337	309
11	97	96
12	174	175
13	128	127
14	36	40
15	48	48
16	103	110
17	96	102
18	113	121
19	54	59
20	76	80
21	41	45
22	33	39
H,K=	2	2
0	152	167
1	92	97
2	115	109
3	534	528
4	96	106
5	499	459
6	252	230
7	68	76
8	150	141
9	120	114
10	68	60
11	191	176
12	128	128
13	198	203
14	29	29
15	188	191
16	41	52
17	60	64
18	87	82
19	27	29
20	20	23
21	39	43
H,K=	3	2
0	392	383
1	442	427
2	304	296
3	153	148
4	48	39
5	161	156
6	117	117
7	198	188
8	392	354
9	220	209
10	219	206
11	159	154
12	78	75
13•	15	16
14•	8	15
15	90	89
16	107	107
17	53	67
18	100	99
19	66	67
20	83	87
21	23	28
H,K=	4	2
0	117	124
1	159	149
2	139	139
3	238	243
4	337	331
5	75	86
6	103	99
7	240	206
8	99	100
9	30	37
10	34	34
11	94	88
12	114	115
13	104	107
14	164	168
15	90	98
16	47	51
17	43	50
18	30	36
19•	19	18
20	29	38
H,K=	5	2
0	103	118
1	226	230
2	177	180
3	120	116
4	44	41
5	54	56
6	110	116
7	195	180
8	87	88
9	166	163
10	111	103
11	101	98
12	62	66
13	22	21
14	26	31
15	46	51
16	66	68
17	62	66
18	26	27
19	72	81
H,K=	6	2
0	86	93
1	80	82
2	129	134
3	22	25
4	113	125
5	48	57
6	203	205
7	117	119
8	46	52
9	47	54
10	34	47
11	83	84
12	79	88
13	40	51
14	61	63
15•	15	26
16	54	63
17	33	41
18•	15	19
H,K=	7	2
0	44	52
1	136	141
2	107	113
3	160	171
4	32	40
5	87	94
6	23	27
7	64	70
8	32	43
9	160	136
10•	8	21
11	87	76
12•	15	15
13	55	52
14•	15	16
15	23	20
16	23	27
H,K=	8	2
0•	8	17
1	36	38
2	60	54
3	27	29
4	136	129
5	47	49
6	79	76
7	55	59
8	40	34
9	51	43
10•	19	34
11•	0	11
12	32	36
13	32	32
14	55	52
H,K=	9	2
0	27	37
1	60	58
2•	0	13
3•	0	5
4•	15	14
5•	15	19
6•	15	20
7	51	45
8•	0	10
9	23	21
10•	8	12
11	36	32
H,K=	10	2
0•	0	5
1•	19	18
2	40	43
3•	12	16
4	32	33
5	23	26
6	44	40
H,K=	0	3
1	224	221
2	249	250
3•	12	2
4	429	407
5	334	320
6	415	377
7	94	106
8	135	132
9	128	108
10•	0	5
11	58	67
12	180	185
13	51	55
14	189	202
15	73	81
16	101	109
17	26	22
18	62	72
19	53	59
20•	0	5
21•	0	10
22	71	76
H,K=	1	3
0	136	144
1	506	502
2	167	161
3	71	65
4	205	189
5	82	84
6	103	84
7	60	66
8	163	161
9	312	305
10	61	57
11	305	280
12	92	93
13	106	110
14	64	81
15•	0	14
16	61	69
17	104	124
18	43	50
19	94	107
20	32	32
H,K=	2	3
0	29	15
1	209	197
2	163	151
3	157	149
4	505	477
5	237	214
6	287	273
7	152	144
8	178	169
9	217	222
10•	19	23
11	27	29
12	195	190
13	117	118
14	149	167
15	62	97
16	127	157
17	62	67
18	50	46
19	55	54
20	29	29
21	30	35
H,K=	3	3
0	254	240
1	132	131
2	244	223
3	166	163
4	173	164
5	191	178
6	41	52
7	173	167
8	251	250
9	238	230
10	107	109
11	75	77
12	80	91
13	66	66
14	64	73
15	78	75
16	37	33
17	34	32
18	99	100
19	97	89
20	54	52
21	47	51
H,K=	4	3
0	89	92
1	153	139
2	89	88
3	235	217
4	167	165
5	128	119
6	153	152
7	97	102
8	57	51
9	73	71
10	44	43
11•	0	12
12	57	58
13	114	119
14	136	146
15	72	80
16	47	54
17	48	51
18	47	56
19•	16	25
H,K=	5	3
0	171	165
1	157	153
2	198	188
3	128	123
4	71	70
5	122	122
6	32	27
7	33	29
8	214	192
9	138	126
10	223	189
11	40	41
12	44	41
13	94	90
14	48	50
15	43	44
16	58	59
17	73	84
18	68	73
H,K=	6	3
0	46	49
1	100	100
2	53	51
3	78	81
4	39	40
5	157	160
6	46	55
7	68	66
8	53	54
9	58	61
10	20	21
11	20	16
12	47	57
13	85	105
14•	18	23
15	53	65
16	23	24
17	22	29
18•	9	21
H,K=	7	3
0	163	157
1	39	44
2	39	52
3	39	40
4•	0	22
5•	0	32
6	25	36
7	25	41
8	25	42
9•	0	20
10	66	79
11•	0	11
12	39	57
13•	12	25
H,K=	8	3
0•	0	20
1•	0	9
2•	0	27
3	53	67
4•	0	24
5	78	85
6•	0	20
7	33	34
8	33	33
9	30	50
10•	0	21
11	33	36
H,K=	9	3
0	64	67
1	39	45
2•	0	2
3	39	34
4	39	44
H,K=	10	3
0•	0	1
1•	0	11
2	25	31
3•	0	21
H,K=	0	4
0	321	335
1	247	239
2	547	629
3	234	231
4•	12	3
5	258	248
6	64	69
7	241	228
8	487	456
9	108	103
10	298	283
11	55	59
12	248	240
13	113	122
14	43	46
15	71	75
16	150	153
17	71	66
18	62	71
19•	0	5
20	82	94
21	33	40
H,K=	1	4
0	133	124
1	85	96
2	273	280
3	323	352
4	217	219
5	181	187
6	182	170
7	364	355
8	252	237
9	65	61
10	140	125
11	150	146
12	157	150
13	121	120
14	22	34
15	94	98
16	79	86
17	47	54
18	62	64
19	39	45
20	43	51
H,K=	2	4
0	23	28
1	164	163
2	452	444
3	270	260
4	83	86
5	115	113
6	184	194
7	174	182
8	214	228
9	48	54
10	207	214
11	103	109
12	104	111
13	51	55
14	37	36
15	129	129
16	76	84
17	44	52
18	41	45
19•	16	21
20	47	63
21	37	40
H,K=	3	4
0	185	180
1	191	179
2	308	309
3	251	250
4	71	77
5	135	143
6	280	268
7	226	223
8	99	100
9	48	55
10	118	115
11	173	171
12	202	196
13	131	130
14	30	51
15	138	144
16	40	45
17	26	29
18	39	40
19	26	26
20	53	49
H,K=	4	4
0	142	142
1	92	104
2	265	234
3	248	229
4	131	127
5	111	112
6	133	122
7	138	133
8	152	150
9	128	131
10	101	98
11	124	131
12	80	73
13	64	72
14	61	70
15	58	65
16	68	73
17	46	48
18	32	30
19	44	44
H,K=	5	4
0	72	72
1	101	100
2	145	141
3	164	148
4	167	151
5	150	137
6	100	93
7	60	60
8	93	87
9	96	88
10	127	129
11	106	102
12	89	92
13	36	40
14	71	74
15	27	32
16	37	40
17	40	38
H,K=	6	4
0	34	38
1	97	99
2	36	43
3	76	76
4	89	92
5	23	27
6	103	110
7	92	104
8•	13	10
9	106	100
10	61	63
11	57	69
12	37	46
13•	0	9
14	36	43
15	32	42
16	34	44
17•	13	21
H,K=	7	4
0•	0	23
1	36	52
2	29	31
3	36	57
4	90	108
5•	19	23
6	76	95
7	61	69
8	94	97
9	46	60
10	41	52
11•	0	15
12	54	67
13	20	23
14	48	58
H,K=	8	4
0	33	54
1	48	64
2	27	28
3	64	68
4	46	60
5	32	49
6	25	29
7	25	35
8	29	37
9	61	61
10•	0	24
11	23	32
12	20	36
H,K=	9	4
0•	0	21
1	36	41
2	23	37
3	20	24
4•	0	2
5•	0	19
6	53	57
H,K=	10	4
0•	0	10
1	29	35
2•	16	23
3•	12	24
H,K=	0	5
1	484	517
2	260	255
3	62	70
4	86	95
5	121	110
6	37	46
7	164	167
8	150	143
9	217	198
10•	0	8
11	175	165
12	44	43
13	128	132
14	39	32
15•	0	17
16•	0	1
17	118	117
18	43	42
19	86	81
20•	12	14
21	57	74
H,K=	1	5
0	160	159
1	244	203
2	202	191
3	226	213
4	314	310
5	100	107
6	302	281
7	33	41
8	124	117
9	30	21
10	48	49
11	55	59
12	124	125
13	25	32
14	194	174
15	30	41
16	175	162
17	36	35
18	55	58
19	33	44
20	32	20
H,K=	2	5
0	156	160
1	293	284
2	156	159
3	195	213
4	82	83
5	72	73
6	89	90
7	113	122
8	100	103
9	228	232
10	103	105
11	174	174
12	114	115
13	97	103
14	37	49
15	48	59
16	43	43
17	96	97
18	43	54
19	103	104
20	43	49
H,K=	3	5
0	37	40
1	86	94
2	200	199
3	200	209
4	226	235
5	107	126
6	54	49
7	128	132
8	104	103
9	44	57
10	40	43
11	33	44
12	30	27
13	106	107
14	140	141
15	61	70
16	58	58
17	64	61
18	27	31
19•	0	4
20•	0	8
H,K=	4	5
0	29	39
1	114	111
2	180	168
3	85	83
4	43	38
5	43	56
6	33	42
7	51	47
8	72	68
9	167	162
10	85	94
11	48	44
12	44	45
13	99	94
14	33	35
15	37	35
16	27	18
17	26	31
18	47	48
H,K=	5	5
0•	13	4
1	39	46
2	44	42
3	180	163
4	161	154
5	125	125
6	53	55
7	78	73
8	103	97
9	106	99
10	37	40
11	43	43
12	48	44
13	100	94
14	72	66
15	114	105
16	33	33
17	39	39
H,K=	6	5
0	219	224
1	58	61
2	32	45
3	29	28
4	47	51
5	50	53
6	58	63
7	25	32
8	85	89
9	44	45
10	47	54
11	30	41
12	76	87
13	30	41
14	20	28
15•	13	20
16•	12	14
H,K=	0	6
0	213	204
1	252	241
2	195	195
3	192	192
4•	15	21
5	266	247
6	41	45
7	202	191
8	146	139
9	34	34
10	258	243
11	100	93
12	75	83
13	173	172
14•	0	11
15	41	44
16	127	118
17	48	53
18	29	30
19	29	29
20	75	81
H,K=	1	6
0	156	156
1	149	135
2	167	165
3	256	239
4	61	55
5	224	225
6	78	76
7	180	167
8	97	101
9	46	41
10	79	81
11	166	152
12	127	129
13	100	95
14	57	57
15	111	107
16	40	50
17	61	76
18	54	58
19	41	47
20	22	27
H,K=	2	6
0	227	237
1	100	112
2	182	171
3	244	248
4	47	47
5	72	85
6	25	27

TABLE 2. (Continued)

L	FO	FC	L	FO	FC	L	FO	FC	L	FO	FC	L	FO	FC	L	FO	FC	L	FO	FC	L	FO	FC	L	FO	FC	L	FO	FC
7	166	171	15	39	35	10	58	67	6	47	59	1	82	84	7	36	28	6	76	38	1	33	49	7•	11	17	H,K=	0	12
8	223	228	H,K=	6	6	11	40	49	7	107	118	2	82	91	8•	0	7	7	76	75	2	82	101	8•	11	5	0•	0	23
9	29	16	0	44	48	12	64	70	8•	18	22	3	192	188	9	106	88	8	29	35	3	43	43	9	44	44	1•	0	8
10	171	184	1	92	94	13	104	107	9•	18	21	4	128	133	10	32	34	9	20	20	4	23	21	10	37	31	2•	11	23
11	108	117	2	110	107	14	114	119	10•	12	20	5	25	28	11	117	101	10	46	42	5•	0	5	11	80	75	3	124	106
12	27	23	3	50	55	15	46	53	11	27	32	6	72	79	12	30	32	11	48	39	6	47	61	12•	0	10	4•	11	9
13	71	72	4	43	49	16	75	85	12•	18	16	7	46	58	13	79	73	12•	18	23	7•	0	18	13•	0	9	5	34	22
14	23	27	5	65	74	17	43	49	13	25	37	8	131	136	14	39	47	13	33	37	8	47	54	H,K=	1	11	6	37	23
15	57	68	6	29	35	18	22	20	14•	18	33	9	71	87	15	79	77	H,K=	5	9	9•	0	14	0	27	35	7	85	80
16	47	36	7	39	47	H,K=	3	7	H,K=	0	8	10	73	78	16•	18	18	0	65	73	10	76	81	1	43	44	8•	19	25
17	23	20	8	32	38	0	157	168	0	262	240	11	27	35	H,K=	1	9	1	44	49	11	50	58	2	57	64	9•	8	0
18	40	49	9	82	87	1	120	120	1	103	107	12	120	101	0	33	39	2•	0	6	12	39	39	3	39	41	10•	0	0
19	40	41	10	23	30	2	106	118	2	39	41	13	60	58	1	138	139	3	26	36	13•	18	27	4	46	61	H,K=	1	12
H,K=	3	6	11	47	54	3	44	43	3	69	71	14	30	44	2	76	85	4	76	74	14•	19	28	5	20	23	0	39	33
0	117	123	12	30	35	4	54	63	4•	0	4	15	51	51	3•	15	20	5	51	52	H,K=	3	10	6	78	79	1	33	42
1	97	97	13•	18	18	5	60	70	5	312	298	16•	0	12	4	113	107	6	60	52	0•	0	8	7	20	24	2	114	98
2	79	92	14	43	54	6	33	39	6	110	109	17•	0	8	5	65	64	7	58	56	1	124	120	8	41	45	3•	0	12
3	113	115	15	29	40	7	118	120	7	23	29	H,K=	4	8	6	85	87	8	39	44	2	78	81	9	61	47	4	41	46
4	206	206	H,K=	0	7	8	56	86	8	107	100	0	46	39	7	61	69	9	20	23	3	106	101	10	43	47	5	34	46
5	251	256	1	122	109	9	54	65	9	36	37	1	93	93	8	114	109	10	36	41	4	44	60	11	22	14	6•	15	14
6	166	168	2	159	160	10	72	61	10•	0	12	2	53	61	9	64	76	11	30	43	5	82	75	12	58	62	7•	16	14
7	168	177	3•	16	30	11	97	69	11	72	67	3	110	97	10	47	45	H,K=	6	9	6	26	24	H,K=	2	11	8	50	45
8	133	142	4	66	62	12	60	65	12	50	40	4	160	159	11	65	67	0	62	63	7	44	34	0•	0	13	9•	13	19
9	79	83	5	60	56	13•	0	13	13	166	135	5	85	86	12	73	63	1	29	23	8	51	45	1	50	57	10	48	47
10	131	121	6	393	371	14	26	25	14	36	23	6	41	51	13•	0	6	2	25	27	9	25	17	2	30	39	H,K=	2	12
11	29	35	7	159	149	15	32	36	15	89	76	7	61	59	14	62	62	3•	0	25	10•	0	11	3	30	29	0	27	39
12	46	50	8	76	67	16	41	50	16	22	18	8	115	117	15•	13	19	4•	12	13	11	34	38	4	86	93	1•	16	21
13	157	157	9	27	35	17	34	37	17	20	25	9	36	45	16	46	41	5	44	62	12•	19	22	5	40	43	2	22	15
14	79	83	10	68	59	18•	19	21	18	62	71	10	61	56	H,K=	2	9	6	32	34	13	93	85	6	23	27	3	71	73
15	66	63	11	54	42	H,K=	4	7	H,K=	1	8	11•	0	6	0	188	196	7•	18	17	H,K=	4	10	7	55	63	4•	0	5
16	32	31	12	97	89	0	171	178	0	295	276	12	20	27	1	37	38	8	30	37	0	76	65	8	27	39	5•	19	19
17	47	49	13	44	56	1	66	64	1	73	76	13	64	57	2	40	53	9•	0	19	1	111	103	9	48	65	6	48	56
18	48	48	14	65	46	2	108	103	2	100	104	14	62	67	3	117	130	10	47	52	2	53	46	10•	18	14	7	55	51
19	25	25	15	33	41	3	62	70	3	37	43	15	36	34	4	96	110	11	22	29	3	68	58	11	33	41	8	26	22
H,K=	4	6	16	115	111	4	46	46	4	100	102	H,K=	5	8	5	43	56	H,K=	0	10	4	22	25	12•	0	12	9	33	39
0	100	90	17•	11	2	5	68	73	5	149	142	0	27	31	6	80	99	0	194	191	5	50	53	H,K=	3	11	H,K=	3	12
1	173	160	18	51	57	6	177	158	6	72	78	1	121	112	7	64	79	1	39	31	6•	12	19	0	80	74	0	40	31
2	133	141	19	44	56	7	58	54	7	48	48	2	68	68	8	23	13	2	82	75	7	20	23	1	26	25	1	33	23
3	114	112	H,K=	1	7	8	47	51	8	133	125	3	43	52	9	71	80	3•	19	32	8	47	37	2•	0	20	2	55	41
4	57	56	0	27	38	9	85	88	9	68	79	4	50	55	10	39	39	4	69	59	9	51	57	3•	0	29	3	44	45
5	136	125	1	180	171	10•	19	32	10	207	210	5	27	37	11	76	81	5	110	86	10	53	42	4	47	45	4	54	46
6	140	137	2	82	87	11•	19	26	11•	0	6	6	20	24	12	60	66	6	157	138	11	36	33	5	46	53	5	40	29
7•	19	22	3	192	193	12	92	81	12	53	52	7	40	52	13	27	36	7	46	46	H,K=	5	10	6	72	77	6	40	35
8	117	115	4	136	125	13	44	45	13	40	39	8	48	50	14	29	33	8	108	86	0	23	24	7	22	35	7	58	56
9	249	253	5	60	59	14	48	45	14	25	26	9	82	82	15•	16	18	9•	12	14	1•	0	7	8	26	33	8	58	58
10	61	57	6	92	98	15	40	47	15•	16	20	10	58	44	16	30	39	10	26	30	2	71	70	9	54	49	H,K=	4	12
11	37	40	7	121	115	16	44	48	16	61	59	11	76	66	H,K=	3	9	11	25	23	3	23	23	10	34	39	0•	0	17
12	108	104	8	94	96	H,K=	5	7	17	41	48	12	40	33	0	58	71	12	108	93	4	57	60	11•	13	17	1•	19	32
13	69	64	9	142	135	0	65	67	18	62	66	13	30	25	1	99	103	13	46	36	5	23	20	H,K=	4	11	2•	13	18
14	22	21	10	68	77	1	125	113	H,K=	2	8	H,K=	6	8	2	52	56	14	27	20	6	46	47	0•	0	12	H,K=	0	13
15	41	36	11	178	164	2	80	79	0	152	155	0	51	57	3	46	42	15•	13	15	7	33	29	1	40	34	1	75	53
16	57	67	12	25	33	3	107	97	1	75	95	1	23	30	4	48	62	H,K=	1	10	8	37	32	2	47	44	2•	13	13
17	48	59	13	103	105	4	55	62	2•	0	13	2	32	41	5	95	102	0	39	30	9	33	29	3	27	24	3	68	68
H,K=	5	6	14	75	75	5	69	67	3	114	126	3	23	26	6	111	113	1	55	63	H,K=	6	10	4	41	34	4	29	26
0	69	63	15	34	32	6	60	61	4	33	44	4	61	75	7	40	48	2	20	32	0	53	44	5	30	23	5	25	26
1	89	80	16	33	39	7•	0	15	5	153	168	5	27	28	8•	0	26	3	68	77	1	43	47	6	37	41	6	60	65
2	69	71	17	60	52	8	83	83	6	104	119	6	61	72	9	61	61	4	76	52	2•	0	12	7	69	63	H,K=	1	13
3	135	128	18•	16	22	9	65	58	7	99	105	7	65	70	10•	12	25	5	143	140	3	34	38	8	94	99	0•	19	10
4	180	170	19	82	86	10	48	60	8	54	50	8•	0	5	11	60	50	6•	0	26	4	25	22	H,K=	5	11	1	54	56
5•	16	18	H,K=	2	7	11	78	70	9	29	37	9	25	25	12	65	57	7	68	75	5•	0	6	0	27	33	2•	15	9
6	101	92	0	37	40	12	42	52	10	57	66	10•	18	19	13	20	27	8•	13	33	6	27	29	1	26	29	3	34	38
7	107	98	1	56	71	13	43	39	11	43	51	11•	16	16	14	28	28	9	26	31	7	61	63	2•	0	14	4	25	15
8	80	72	2	113	121	14	26	19	12	22	31	12	40	46	15	33	32	10	58	64	8•	12	9	3	40	49	5•	0	5
9	65	66	3	104	110	H,K=	6	7	13	79	82	H,K=	0	9	H,K=	4	9	11•	16	61	H,K=	0	11	4•	0	15	H,K=	2	13
10	46	35	4	206	216	0•	0	3	14	47	53	1	178	165	0	115	130	12	37	47	1	61	57	5	23	32	0•	11	11
11	53	59	5	143	154	1	41	61	15	58	66	2	36	44	1	32	31	13	27	28	2•	0	6	H,K=	6	11	1	34	34
12	43	46	6	72	82	2	61	67	16	32	32	3	30	31	2	53	56	14•	0	4	3•	0	1	0	30	39	2	46	51
13•	0	15	7	161	160	3	58	67	17	43	46	4	58	58	3	57	64	15	66	75	4	22	18	1•	0	9	3	43	45
14	69	62	8	94	110	4	25	22	H,K=	3	8	5	39	45	4	89	83	H,K=	2	10	5	30	31	2•	9	14			
15	36	32	9	54	65	5	41	60	0	199	192	6	104	102	5	65	71	0	107	111	6	121	96	3•	8	7			

index now decreased to 0.073 for all the observed reflections, and 0.081 if non-observed reflections were included.

The atomic scattering factors used in the calculations were taken from The International Tables for X-Ray Crystallography;[13] that for the bromine atom was corrected for $\Delta f'$ (-0.9).[14] In the least-squares refinement, the weight assigned for each reflection was 1.0 for most of them, and 0.2 for a few of the weakest ones (marked by asterisks in Table 2). The damping factors for the shifts of parameters were used in the least-squares refinement; 0.7 was applied for all the parameters except for those of the hydrogen atoms, for which 0.2 was used.

The final atomic parameters are listed in Table 1; the observed and the calculated structure factors, in Table 2, and the three-dimensional electron-density map and the difference Fourier function, in Figs. 1 and 2. The standard deviations of the positional parameters, as listed in Table 1, are from 0.007 to 0.012 Å for C, N and O, and 0.13 Å for H.

The Patterson functions were calculated on the NEAC 2101 of this Institute with programs written by T. Takano and Y. Nishi of this Institute. The three-dimensional computations were done on the IBM 7090 through the "UNICON" project, with programs written by the present authors.

Absolute Configuration

In order to establish the absolute configuration of the glutamic acid, the anomalous dispersion effect due to the bromine atom was used. Though the effect is small for the Cu$K\alpha$ radiation ($\Delta f'=-0.9$ and $\Delta f''=1.5$),[14] about 30 pairs of F_{H} and $F_{\bar{\mathrm{H}}}$ values were found to show fairly significant differences, $(F_{\mathrm{H}}-F_{\bar{\mathrm{H}}})$. 32 pairs of reflections were used in the calculations; all but two indicated that the glutamic acid has the D-configuration. The structure factors calculated on the basis of the D-configuration by using $\Delta f'=-0.9$ and $\Delta f''=1.5$ are listed in Table 3, together with their

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[13] "International Tables for X-Ray Crystallography," Vol. III, The Kynoch Press, Birmingham (1962), p. 201.

[14] C. H. Dauben and D. H. Templeton, *Acta Cryst.*, **8**, 841 (1955).

TABLE 3. OBSERVED AND CALCULATED STRUCTURE FACTORS (×10) USED FOR THE DETERMINATION OF THE ABSOLUTE CONFIGURATION

			Obs.		Calcd.	
h	*k*	*l*	F_H	$F_{\bar{H}}$	F_H	$F_{\bar{H}}$
1	1	2	66	95	51	79
1	1	7	117	96	111	90
1	2	11	92	103	92	96
1	2	19	59	52	62	57
1	3	3	71	66	77	55
1	3	7	63	57	76	70
1	3	10	56	61	54	63
1	3	12	103	96	97	87
1	4	9	57	73	60	67
2	1	10	96	105	94	101
2	1	14	112	123	118	129
2	1	16	131	126	146	138
2	2	7	68	77	76	79
2	3	7	156	140	151	139
2	7	1	64	59	74	67
3	1	1	123	131	130	146
3	1	8	64	52	68	51
3	1	9	59	46	60	48
3	2	4	41	46	41	48
3	3	6	52	42	55	50
3	5	1	94	87	94	91
4	1	5	133	152	115	133
4	1	6	124	112	115	101
4	1	9	101	120	99	114
4	2	2	137	112	142	136
4	2	6	116	94	110	87
4	2	8	94	105	99	104
4	2	15	84	77	103	95
4	3	2*	98	89	89	90
4	4	1	114	92	112	94
5	1	9*	71	81	76	75
6	1	3	52	43	54	46

* See text.

TABLE 4. BEST PLANES

(a) Coefficients for the planes. Each plane is represented by $lX + mY + nZ + p = 0$, where X, Y and Z are coordinates in Å.

Plane	l	m	n	p	
1	0.5545	0.0317	−0.8316	1.6072	(α-carboxyl group)
2	0.7414	−0.3457	−0.5751	3.2053	(γ-carboxyl group)
3	−0.0997	0.5379	−0.8371	0.6604	(phenyl group)
4	−0.9521	0.0295	0.3045	0.2824	(three neighbors of W(1))
5	0.0417	−0.7205	−0.6922	5.7364	(three neighbors of W(2))

(b) Displacements of atoms from the planes (Å)

Plane 1		Plane 2		Plane 3		Plane 4		Plane 5	
O(1)	0.002	O(3)	−0.002	C(7)	−0.007	O(4)	0	O(3)	0
O(2)	0.002	O(4)	−0.003	C(8)	−0.004	O(1)	0	W(2)′	0
C(1)	−0.006	C(4)	−0.002	C(9)	0.010	Br	0	Br	0
C(2)	0.002	C(5)	0.007	C(10)	−0.007	W(1)*	−0.09	W(2)*	0.199
N*	−0.094	C(3)*	0.643	C(11)	−0.004				
C(3)*	−1.239			C(12)	0.013				
C(6)*	1.376			C(6)*	−0.077				

* Shows that the atom was not included in the evaluation of the equation of the plane.

observed structure factors, the two pairs indicating another configuration being marked by asterisks; the error index for these 64 reflections is 0.076. Thus this amino acids was determined to be D-(+)-2-benzylglutamic acid, as is shown in Fig. 3. This configuration is also favored by Izumi and his collaborators from their studies of the asymmetric syntheses.[15]

Discussion

All the bond distances, angles and other important intra- and intermolecular approaches below 4.0 Å were calculated from the atomic coordinates listed in Table 1, and the equations of the best planes of several planar groups were evaluated, the latter being listed in Table 4. These computations were performed on the HITAC 5020 at the

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[15] Y. Izumi, Private communication.

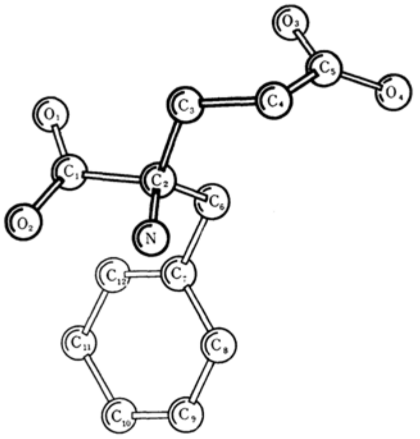

Fig. 3. The absolute configuration: D-(+)-2-benzylglutamic acid.

University of Tokyo using a program written by the present authors.

Figure 4 shows the bond distances and angles in the present glutamic acid. The standard deviations of the bond lengths and angles among C, N and O are from 0.010 to 0.017 Å and from 0.7° to 1.0° respectively. The C(2)–NH_3^+ bond distance, 1.51 Å, is a little longer than the average value, 1.493 Å,[*3] found in many amino acids, but the difference may not be significant. The nitrogen atom is nearly coplanar with the α-carboxyl group, the displacement of the atom from the plane being 0.09 Å. The C–C single bonds range from 1.52 to 1.56 Å, which are quite normal. Also normal are the shape and the size of the phenyl group; the C–C bond lengths range from 1.38 to

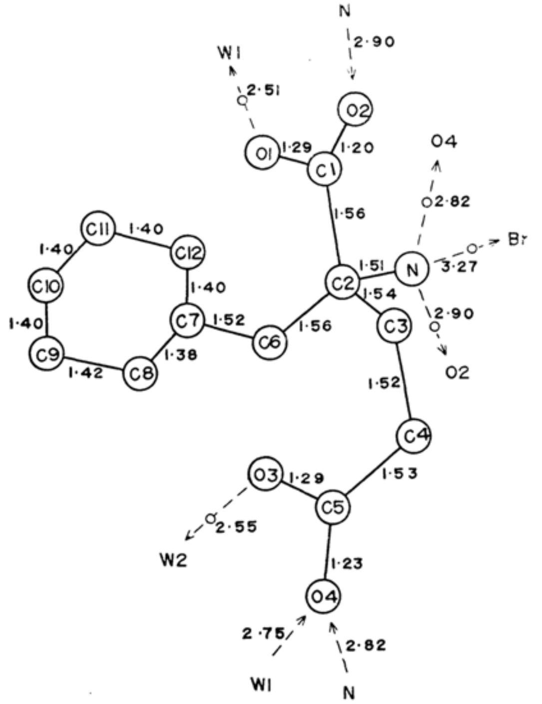

Fig. 4(a).

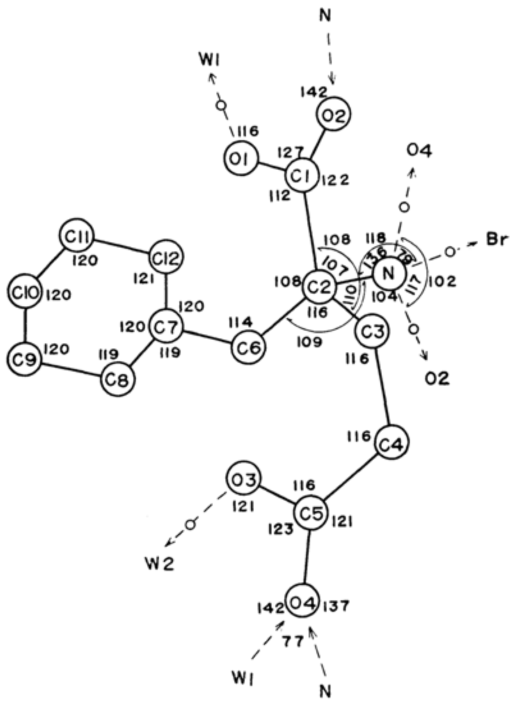

Fig. 4(b).

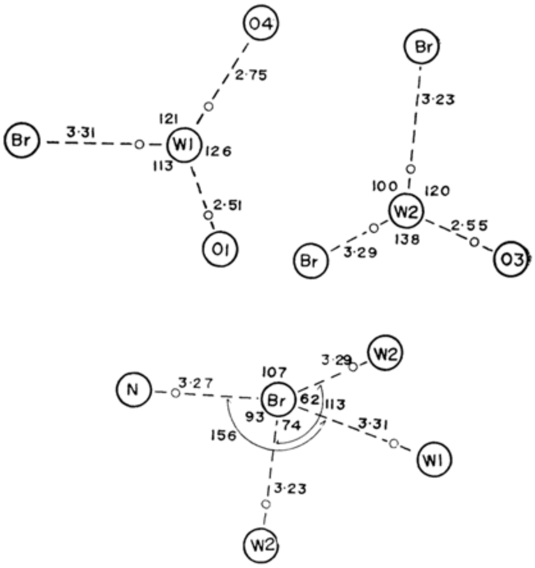

Fig. 4(c).

Fig. 4. Bond lengths (Å) and angles (°). The broken lines show the hydrogen bonds.

[*3] This is the average of the C-NH_3^+ bond distances in amino acids, the crystal structures of which have been analyzed by using three-dimensional intensity data.

1.42 Å, with an average of 1.40 Å, while the bond angles range from 119° to 121°. The group is planar, as is shown in Table 4.

There are some interesting and significant variations in the bond angles in the carbon skeleton of the present glutamic acid. The bond angles, C(2)–C(6)–C(7) (114°), C(2)–C(3)–C(4) (116°), and C(3)–C(4)–C(5) (116°), are significantly larger than the regular tetrahedral angles, but such large differences are not so unusual in such substances. The C(6)–C(2)–C(3) angle, 116°, is also large, but the other five bond angles around the C(2) atom are all close to 109.5°. Among the four substituents of the C(2) atom, the propionic acid residue and the benzyl group are much larger than the α-carboxyl and the α-amino groups. Thus the wide angle of C(6)–C(2)–C(3) is due to the repulsion force between the two large substituents; the bond angles around C(3), C(4) and C(6) mentioned above may also have a somewhat similar significance. The dimensions of two carboxyl groups are almost equal to each other. O(1) and O(3) have hydrogen atoms, and C(1)–O(1) and C(5)–O(3) are both 1.29 Å. The bond distances of C(1)–O(2), 1.20 Å, and C(5)–O(4), 1.23 Å, are close to the length of the pure double bond between the carbon and the oxygen atom; O(4) is the acceptor of two hydrogen bonds, while O(2) accepts only one. In general, these carboxyl groups are very similar to those found in glutamic acid hydrochloride[8] and in many carboxylic acids.

Hirokawa[7] gave an interesting discussion of the carbon-chain configurations in β-glutamic acid,[7] glutamic acid hydrochloride[8], and glutamine.[9] Since then, the structure of glutathione (γ-L-glutamyl-L-cysteinyl-glycine) has been determined;[10] thus, it may be of some significance to extend his discussion by including the present crystal and the glutamyl residue in glutathione. In Fig. 5, the molecular configurations in the five crystals are shown for the sake of comparison. We can summarize the following features:

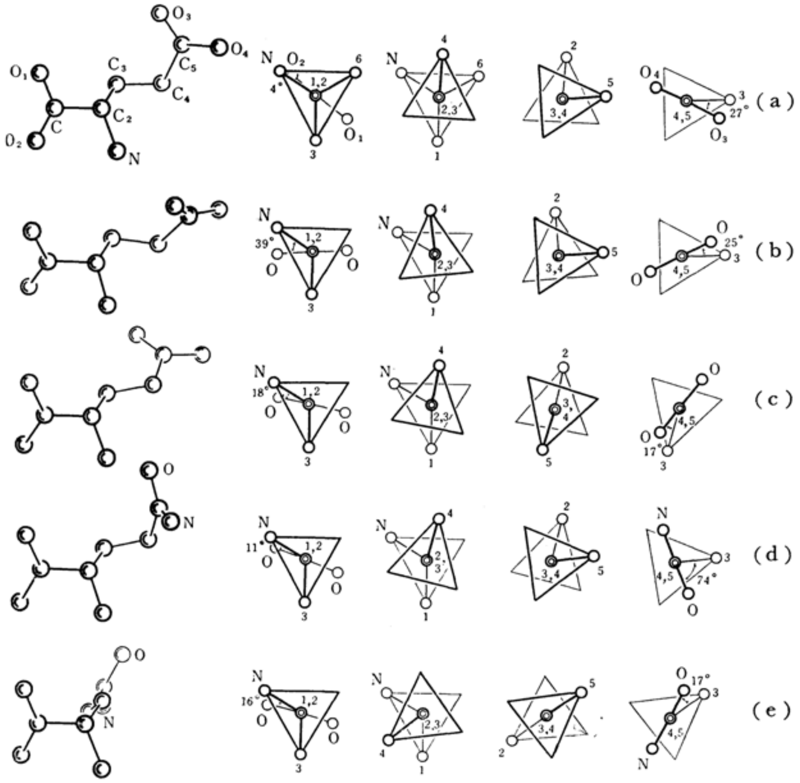

Fig. 5. Carbon-chain configurations of some related compounds. The first column shows molecules viewed down on the planes of C′–C$_\alpha$–N (C(1)–C(2)–N). In the second to the last, the arrangements of atoms nearest to the perticular bonds are shown. The second shows α-carboxyl, α-N, C$_\beta$, H$_\alpha$ and two H$_\beta$'s viewed down the C$_\alpha$–C′ bond, the third down the C$_\beta$–C$_\alpha$, and so on. The bold lines show the atoms on the upper side, and the positions of hydrogen atoms are idealized. The triangles of N, C′ and H$_\alpha$ have the same orientation in all the molecules, and the orientations of the others are correlating with the first. L-Amino acids are figured for all the molecules. A part of the figure is after Hirokawa.[7] (a) present crystal, (b) β-glutamic acid, (c) glutamic acid hydrochloride, (d) glutathione, (e) glutamine.

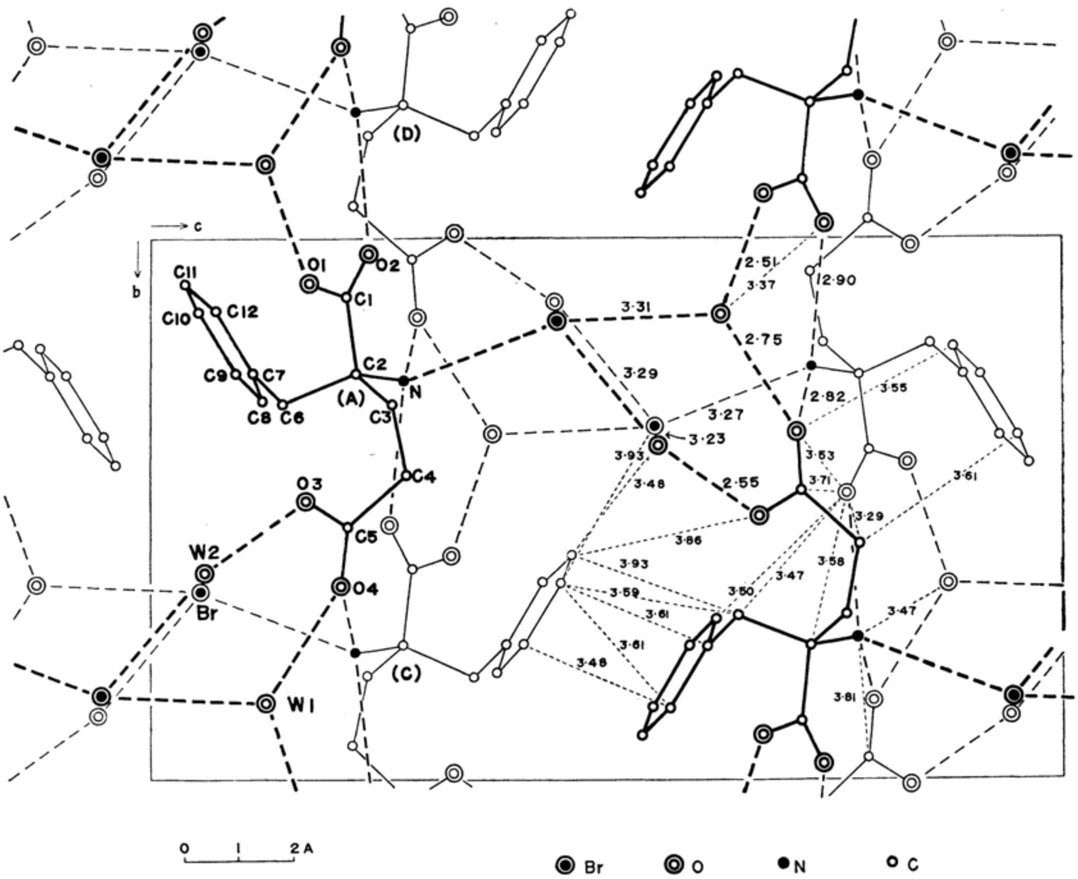

Fig. 6. A drawing of the structure viewed along the a axis. The broken lines show the hydrogen bonds. Some of the short intermolecular approaches are shown.

(1) The arrangement of C(1), α-N and C(4) about the C(2)-C(3) bond causes one of the most distinct differences in the molecular configurations. This is the case not only in these amino acids, but also in all the other amino acids and peptides. Recently Ramachandran and Lakshminarayanan[16)] have found some systematic tendencies (maybe rules) in the relative arrangements of the α-carboxyl, α-amino groups and γ-atoms around the C_α-C_β bonds in some amino acids and peptides in the crystals.[*4] Among the present amino acids, C(4) is in the gauche position to both C(1) and α-N in glutamine, while in the other four, C(4) is in the trans position to C(1) and gauche to α-N. From the viewpoint of Ramachandran and Lakshminarayanan, therefore, the latter seems to be a rule for glutamic acids. No rules, however, can be found for glutamines, because glutathione is an *N*-substituted glutamine.

(2) The displacements of the α-N atoms from the carboxyl planes are 0.09, 0.82, 0.43, 0.35, and 0.28 Å in the present crystal, β-glutamic acid, glutamic acid hydrochloride, glutamine, and glutathione respectively; thus α-N is nearly coplanar with the carboxyl group in the present crystal, but in the other four the displacements are significant.

(3) C(2) and C(5) can be in either the trans or the gauche position about the C(3)-C(4) bond. The side chain in glutamic acid hydrochloride is roughly planar, including C(1) and C(2), and in glutamine the side chain and C(2) are roughly coplanar, while in the other three the side chains are not planar because of the internal rotations of the C(3)-C(4) bonds.

(4) The angles between the two planes, C(3)-C(4)-C(5), and the γ-carboxyl groups (or the amide groups in glutamine and glutathione) are not very large except in the case of glutathione; in the latter the large size may be due to the rather large side group in the cysteinyl residue.

(5) Thus, no pairs of the five molecules are essentially the same. The differences are due to

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16) G. N. Ramachandran and A. V. Lakshminarayanan, *Biopolymers,* **4**, 495 (1966).

[*4] In this report C(2) corresponds to C_α in the usual nomenclature for the atoms in amino acids, and so on.

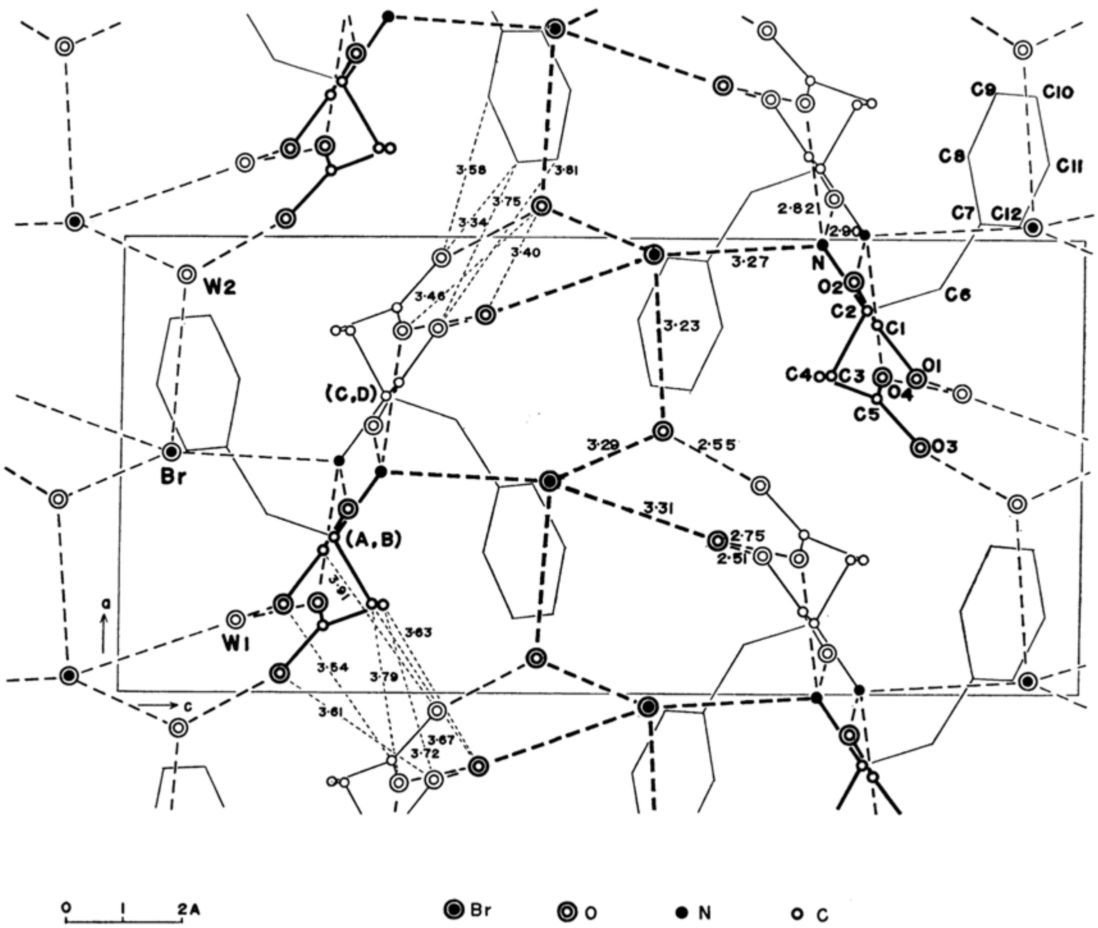

Fig. 7. A drawing of the structure viewed along the b axis.

the internal rotations of all the C–C bonds.

The arguments given above support the conclusion of Hirokawa[7] that the carbon-chain configurations in the related compounds depend more or less on the effects of the surrounding molecules, especially on the modes of hydrogen bonds at the terminal groups. Analogous situations may be expected in aspartic acid and asparagine; however, there are not yet enough data on these amino acids. A similar "polymorphism of the molecular configurations" due to the hydrogen bonds has been found not only in other amino acids (for example, arginine dihydrate, arginine monohydrochloride monohydrate, and arginine monohydrochloride),[17] but also in other compounds (*e. g.*, ethylenediamine and tetramethylenediamine).[18] In other amino acids, methionine[19] and isoleucine,[20] the configurations of the side chains have also been found to be different in several crystal modifications, but this may be due to the van der Waals forces rather than to the hydrogen bonds.

The present amino acid is phenylalanine with a propionic acid residue substituted at the α-carbon atom. The phenyl group protrudes laterally from the glutamic acid residue. The dihedral angle between the phenyl and the α-carboxyl groups is 49°. In the review by Ramachandran and Lakshminarayanan[16] mentioned above, it is found that C_γ in tyrosine and phenylalanine is in the trans position to α-N with respect to the C_α–C_β bond, while in tryptphane C_γ is in the gauche position to both the carboxyl group and α-N or in the trans position to the carboxyl group. Besides, in histidine (three crystals, hydrochloride salt[21] and two Zn salts[22,23])

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17) G. N. Ramachandran, S. K. Mazumdar, K. Venkatesan and A. V. Lakshminarayanan, *J. Mol. Biol.*, **15**, 232 (1966).

18) T. Ashida and S. Hirokawa, *Acta Cryst.*, **16**, 841 (1963).

19) A. McL. Mathieson, *ibid.*, **5**, 332 (1952).

20) J. Trommel and J. M. Bijvoet, *ibid.*, **7**, 703 (1954).

21) J. Donohue, L. R. Lavine and J. S. Rollett, *ibid.*, **9**, 655 (1956).

22) M. M. Harding and S. J. Cole, *ibid.*, **16**, 643 (1963).

23) R. H. Kretsinger, F. A. Cotton and R. F. Bryan, *ibid.*, **16**, 651 (1963).

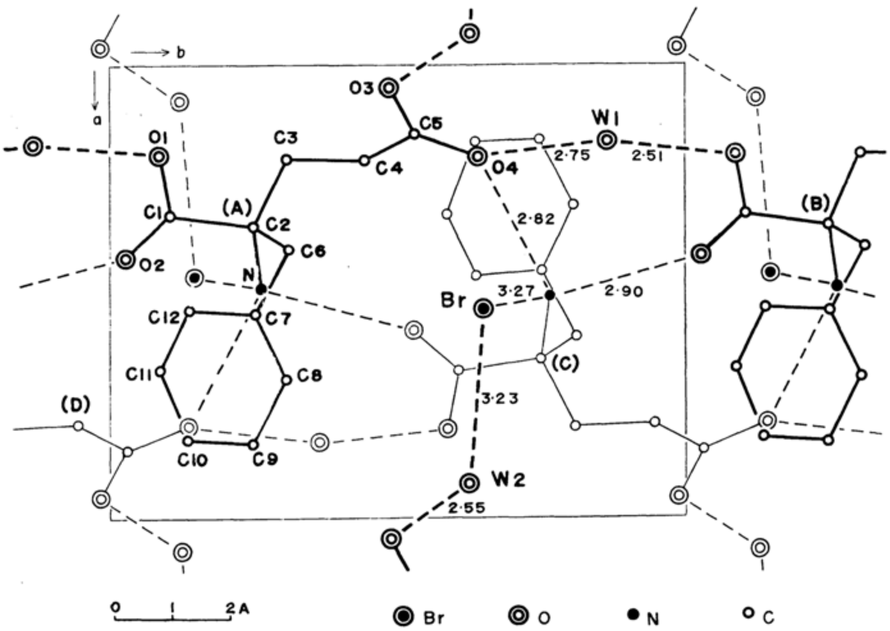

Fig. 8. A drawing of the structure viewed along the c axis. Only the contents between $z=0$ and $z=1/2$ are shown.

C_γ is in the gauche position to both the carboxyl group and α-N. Thus, there seems to be a difference in the conformations of atoms with respect to the C_α-C_β bond, according to whether C_γ belongs to the benzene ring or to the five-membered (basic) ring. In the present case, however, C(7)*5 goes to the gauche position to both C(1) and α-N with respect to the C(2)-C(6) bond. Perhaps the present case may be an exception, because C(2) does not have an hydrogen atom, in contrast to the other amino acids and peptides.

Hydrogen Bonds and Molecular Packing. There are nine independent hydrogen bonds in the crystal shown in Figs. 4, 6, 7 and 8. Among these, two hydrogen bonds between the non-ionized carboxyl groups (donors) and the water molecules (acceptors) seem to be fairly strong, their O—O distances being 2.55 and 2.51 Å. Very few hydrogen bonds of such a type have, however, been reported. A few of the examples which have been reported are 2.49 Å in oxalic acid dihydrate,[24] and 2.537 and 2.503 Å in potassium tetraoxalate dihydrate.[25] Thus, though there are not enough data, the hydrogen bonds between the carboxyl groups (donor) and the water molecules (acceptors) seem to be generally stronger than other types of hydrogen bonds between two oxygen atoms. The dimensions of other hydrogen bonds found in the present crystal are comparable to those reported elsewhere.

The bromide ion is the acceptor of four hydrogen bonds, of which one is from the nitrogen atom, while three are from the water molecules. The arrangement of the four donor atoms of these hydrogen bonds around the bromide ion is far from being tetrahedral.

Two water molecules participate in three hydrogen bonds. Their nearest-neighbor coordinations are shown in Fig. 4c. As is shown in Table 4 and in Fig. 4c, both water molecules have nearly planar and trigonal environments. The displacements of W(1) and W(2) from the planes defined by their three neighbors are only 0.20 and 0.09 Å respectively. This is not unusual in hydrated structures; for example, such coordinations have been found in barbituric acid dihydrate,[26] cytosine monohydrate,[27] and dilituric acid trihydrate.[28] As has been pointed out by Clark,[29] in almost one quarter of the hydrated structures which have been studied the water molecules have planar threefold environments.

The packing scheme in the crystal is rather unique. Generally, in crystals composed of both polar and non-polar groups we have found layers of molecular contacts of polar or ionic parts and,

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*5 C(6) and C(7) correspond to C_β and C_γ respectively if the present amino acid is deemed to be phenylalanine.

[24] F. R. Ahmed and D. W. J. Cruickshank, *ibid.*, **6**, 385 (1953).

[25] D. J. Haas, *ibid.*, **17**, 1511 (1964).

[26] G. A. Jeffrey, S. Ghose and J. O. Warwicker, *ibid.*, **14**, 881 (1961).

[27] G. A. Jeffrey and Y. Kinoshita, *ibid.*, **16**, 20 (1963).

[28] B. M. Craven, S. Martinez-Carrera and G. A. Jeffrey, *ibid.*, **17**, 891 (1964).

[29] J. R. Clark, *Rev. Pure Appl. Chem.*, **13**, 50 (1963).

alternately, molecular contacts composed of non-polar parts. However, this is not the case in the present crystal, there being no layers as such. Rather, there are, roughly speaking, three kinds of approaches between the molecules or the ions; the polar organic part (glutamic acid residue), non-polar organic part (phenyl group), and the part of the water molecule, W(2), and the bromide ion. Around the twofold screw axis at $y=1/4$ and $z=0$, there are only contacts among the phenyl groups due to the van der Waals forces. Around the other twofold screw axis, at $y=3/4$ and $z=0$, the bromide ion and the water molecule W(2) gather together and make a zigzag chain of hydrogen bonds elongated along the screw axis. Glutamic acid residues are located roughly at $z=1/4$ or 3/4. As is shown in Figs. 6, 7 and 8, the A molecule at (x, y, z) is connected to B at $(x, 1+y, z)$ by the hydrogen bonds *via* the nitrogen atom of the C molecule at $(1-x, 1/2+y, 1/2-z)$ and via the W(1) water molecule. The A and C molecules are related to each other by the twofold screw axis at $x=1/2$ and $z=1/4$. Similarly, the C and D molecules are connceted by A and other W(1). Thus, these molecules make an column made of two rows of molecules elongated along the b axis. The contact between the columns along the a axis is due to the van der Waals forces. Besides, these columns are connected indirectly along the a and c axes by many hydrogen bonds *via* the bromide ions and the W(2) water molecules. Thus, the two water molecules and the bromide ion play an important role in building up the complicated three-dimensional network, rather than as spacers.

The authors would like to express their deep thanks to Professor Yoshiharu Izumi and his collaborators in this Institute for supplying material and for their continued interest. Thanks are also due to Dr. Tsunehiro Takano and all the staff in our laboratory for their kind cooperation. The computing time of the IBM 7090 was made available to the authors through the kindness of the "UNICON" project, while that of the HITAC 5020 was made available through the kindness of the Computing Center of the University of Tokyo.