[CONTRIBUTION FROM THE CHEMISTRY DEPARTMENT OF THE UNIVERSITY OF ILLINOIS]

X-RAY INVESTIGATIONS OF OPTICALLY ACTIVE COMPOUNDS

I. A PROOF OF MOLECULAR ASYMMETRY IN OPTICALLY ACTIVE PHENYLAMINOACETIC ACID[1]

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Introduction

An investigation for the purpose of establishing the identity of the *d*- and *l*-forms of a substance capable of being resolved into these optically active antipodes, for the purpose of checking up on the similarity of the active and racemic modifications, and for the purpose of finding out whether, after all, the molecules of an optically active substance are asymmetric as first pictured by Pasteur in 1860, and by Le Bel and van't Hoff in 1874, may at first thought seem futile, since the theories concerning these things are so well established. But, as Stewart[2] says: "—— this state of affairs is not altogether healthy since it tends to repel original minds who find little interest in a subject which is apparently resting on a dead center of perfectness. At the present day it seems fashionable to suppose that certain views are so firmly established that no research into their foundations is worth the labor expended on it . . . it was supposed for many years that the composition of the atmosphere was definitely settled—and then the discoveries of Rayleigh and Ramsay showed how little was known of even this common mixture. With this object lesson before them, it is to be hoped that more organic chemists will find time to investigate some of the problems which are passed over by the bulk of workers who seem to place a label in the same category as an explanation."

The x-ray examination of optically active organic compounds is a field which is thus far practically untouched. No one has yet used the powerful rotating crystal method in a study of this type. W. T. Astbury[3] has made a study of *d*-tartaric acid, utilizing axial ratios and angles determined by optical methods, and measuring interplanar spacings by means of the Bragg spectrometer method. He finds that his results confirm the theory of van't Hoff and Le Bel, and that it is not possible to distinguish between the *d*- and *l*-forms of an optically active substance by means of x-ray diffraction methods.

Reis and Schneider[4] have recently presented further x-ray data for tartaric and mesotartaric acids.

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[1] From a part of the thesis submitted by G. R. Yohe to the Graduate School of the University of Illinois in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

[2] Stewart, "Recent Advances in Organic Chemistry," **1927**, Vol. I, p. 18.

[3] Astbury, *Proc. Roy. Soc. London*, **102A**, 506 (1923).

[4] Reis and Schneider, *Z. Krist.*, **69**, 62, 49 (1928).

There are two hundred and thirty space groups according to which crystals may be built. While most of these space groups can be built up of molecules which possess symmetry within their structure, there are a few which will admit of no molecular symmetry. If, in crystallizing, an optically active compound builds its crystalline form according to one of these space groups which will admit of no symmetry of the molecule this may be taken as direct evidence that its molecules are asymmetric. For this study a representative amino acid, phenylaminoacetic acid, was chosen in spite of the fact that no crystallographic or optical data are available in Groth's tables or elsewhere for the active or racemic forms of this compound. One of the chief purposes of the investigation was to show that a unique structural analysis can be made by means of x-ray diffraction results alone and without adopting the invariable practice of depending upon previous crystallographic information. The rotating crystal diffraction method has been made to combine goniometric orientation of crystals and the production of the fruitful layer-line patterns for rotation around three principal axes.

Experimental

A. The Phenylaminoacetic Acid Used.—Phenylaminoacetic acid was being resolved in connection with another investigation, and the *d*-, *l*- and *dl*-forms at hand were subjected to this x-ray examination.

The crude phenylaminoacetic acid was prepared at the University of Illinois by the following reactions[5]

$$C_6H_5CHO + NaCN + NH_4Cl \longrightarrow C_6H_5CHNH_2CN + NaCl + H_2O$$
$$C_6H_5CHNH_2CN + HCl + 2H_2O \longrightarrow C_6H_5CHNH_2COOH + NH_4Cl$$

It was found that the racemic amino acid could be recrystallized from hot dilute pyridine (2 volumes of water to 1 of pyridine), and that by very slow cooling of the solution well-formed crystals could be obtained. These were very small, however, the largest being about one mm. long and less than one mm. in thickness; m. p. 250–252°, uncorr.

The levorotatory form was obtained by following the procedure of Ingersoll and Adams,[6] which is essentially that of Betti and Mayer,[7] of fractional crystallization of the *d*-camphorsulfonate, the *l*-phenylaminoacetic acid *d*-camphorsulfonate being less soluble. Since the *d*-camphorsulfonate hydrolyzes readily in hot water, it was found best to use an excess of *d*-camphorsulfonic acid in this resolution. The separation of the forms was carried out as follows: 110 g. of *dl*-phenylaminoacetic acid, 206 g. of *d*-camphorsulfonic acid and 500 cc. of water were heated together, giving a clear solution which on cooling deposited crystals of the *l*-phenylaminoacetic acid *d*-camphorsulfonate. These were recrystallized from hot water using about 10% excess of *d*-camphorsulfonic acid to prevent hydrolysis and about 2 g. of Norite to decolorize the solution. The *l*-phenylaminoacetic acid was precipitated from a cold, saturated, aqueous solution of the *d*-

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[5] Adams and Marvel, "Organic Chemical Reagents," **1922,** Vol. IV, p. 24.

[6] Ingersoll and Adams, THIS JOURNAL, **44,** 2930 (1922).

[7] Betti and Mayer, *Ber.*, **41,** 2071 (1908).

camphorsulfonate by adding dilute ammonium hydroxide until the solution was faintly alkaline. The crystals, after washing with water and drying, gave a rotation $[\alpha]_D^{20}$ −152° in 0.133 *N* hydrochloric acid; $[\alpha]_D^{20}$ −162.8° in 10% hydrochloric acid; $[\alpha]_D^{20}$ −111° in water, this last value checking that of −111.02° given by Betti and Mayer.[7] It was found that on slow evaporation of a saturated aqueous solution of the *l*-phenylaminoacetic acid, long needle-like crystals formed. One of the most perfect of these was used in the rotating crystal studies; m. p., subl. 245–248°, uncorr.; $[\alpha]_D^{20}$ (in 0.140 *N* hydrochloric acid) −149°. It may be noted here that the rotations observed varied widely with the concentration of the hydrochloric acid used as a solvent. No consistent melting point was obtained, which is in harmony with the results previously published. For example, St. Minovici[8] reports m. p. 227° (subl.); Fischer and Weichhold[9] report m. p. 305–310°; Betti and Mayer[7] report m. p. above 305°.

The *d*-phenylaminoacetic acid was obtained by extraction of the partially resolved (80% *d*-, 20% *dl*-phenylaminoacetic acid) acid precipitated from the mother liquor of the *d*-camphorsulfonate crystallization with ammonium hydroxide. The active form of phenylaminoacetic acid is more readily soluble in hydrochloric acid than the racemic, and is thus extracted from the racemic.[10] The *d*-phenylaminoacetic acid was precipitated by adding dilute ammonium hydroxide. The mother liquor from this precipitation, on standing for several days, yielded needle crystals, one of the most perfect of which was used in the x-ray work; m. p. 242–244°, uncorr.; $[\alpha]_D^{20}$ (in 0.105 *N* hydrochloric acid) +147°.

B. The X-Ray Equipment.—The x-ray tube used was of the Hadding–Siegbahn type equipped with a copper anticathode. It was operated at about 40 kilovolts and a current of about 12 milliamperes, the high potential being supplied by a Wappler special transformer, rectified by a Kenex rectifier. The radiation was not filtered, the K_α radiation of copper predominating to such an extent that filtration was found unnecessary.

A Müller Universal Spectrograph was used. This was equipped with a cylindrical camera of 5-cm. radius, and a goniometer head which greatly facilitated the accurate orientation of the crystal, as well as making it possible to measure the angles between the crystallographic axes by measuring the displacement necessary to bring another crystallographic axis parallel to the axis of rotation.

The time of exposure depended upon the focus of the cathode rays within the x-ray tube. A good focus giving a very intense beam of x-rays made possible the taking of good pictures in one to two hours' exposure, but for poorer focus and hence a less intense x-ray beam exposures of ten hours were necessary.

C. The Technique of Taking the Photographs.—The levorotatory form was studied first. The needle-like crystal was mounted on the goniometer mounting with a small drop of collodion so that the long axis of the crystal was perpendicular to the axis of rotation. The resulting photograph showed the crystal to be improperly aligned. The angle between

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[8] St. Minovici, *Bull. Soc. Chim. Romania*, **2,** 8 (1910).

[9] Fischer and Weichhold, *Ber.* **41,** 1286 (1908).

[10] Unpublished work from this Laboratory.

the two lines of interferences that cross at the position of the central beam was measured, and the crystal displaced half this angle, still keeping the long axis of the crystal perpendicular to the axis of rotation. By this means it was possible to bring the crystal into alignment so that one of the major crystallographic axes was parallel to the axis of rotation. The resulting layer line diagram is reproduced in Fig. 1. The crystal was then displaced 90°, still keeping the long axis of the crystal perpendicular to the axis of rotation. Another typical layer line diagram was thus obtained showing that another major crystallographic axis was now parallel to the axis of rotation, and that the angle between the two axes was 90°. The crystal was then displaced another 90°, this time bringing the long axis of the crystal parallel to the axis of rotation. Again a typical layer line diagram was produced showing that the third crystallographic axis was now parallel to the axis of rotation, and that the angle between this third axis and the plane of the first two must be 90°.

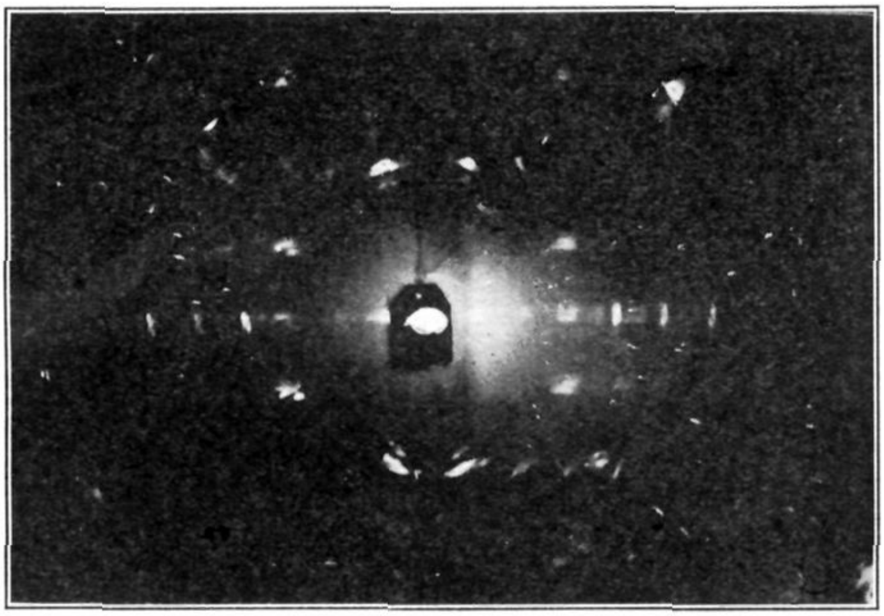

Fig. 1.

In this way the crystal was proven orthorhombic, independently of any optical data, since $\alpha = \beta = \gamma = 90°$. The layer lines of the rotation photographs make possible direct calculation of the "identity periods," or dimensions of the unit cell, and consequently the axial ratio in a manner which is verly clearly explained by Sir William Bragg.[11]

It is of interest to note the size of the crystals used in making these photographs, and others made of the dextrorotatory and racemic modifications. The dimensions of the crystal of *l*-phenylaminoacetic acid were 4 mm. × 1 mm. × 0.1 mm.; those of the crystal of the *d*- form used were 4 mm. ×

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[11] Bragg, "An Introduction to Crystal Analysis," D. Van Nostrand Co., New York, **1929,** p. 41.

0.3 mm. × 0.2 mm.; and those of the crystal of the racemic form were about 2 mm. × 1 mm. × 0.5 mm. Thus it may be seen that very small crystals can be used in work of this type; in fact it is advantageous to use small crystals since the resulting diffraction spots are sharper and can be measured more accurately. Furthermore, a small crystal is more apt to be free from imperfections.

D. Data for *l*-Phenylaminoacetic Acid.—In calculating the identity periods from the layer line photographs, use was made of the equation

$$I = \frac{n\lambda}{\sin \mu}$$

where I is the identity period, n the number of the layer line (*i. e.*, 1st, 2nd, 3rd, ...), λ the wave length of the radiation used (λ Cu K_α = 1.54 Å.), and $\mu = \tan^{-1} e/a$, e being the distance measured on the film from the equator line to the nth layer line, a being 50 mm., the distance from the axis of rotation to the film. The following tables give the results obtained in calculating these identity periods.

TABLE I

DATA FROM FILM REPRODUCED IN FIG. 1 FOR IDENTITY PERIOD ALONG *c* AXIS

Goniometer scale readings: 13° 50', 26° 20'

e, mm.	tan μ	sin μ	n	I, Å.
8	0.1600	0.1579	1	9.74
17	.3400	.3220	2	9.55
27	.5400	.4751	3	9.70
			Average	9.66

TABLE II

DATA FOR IDENTITY PERIOD ALONG *a* AXIS

Goniometer scale readings: 13° 50', 116° 20'

e, mm.	tan μ	sin μ	n	I, Å.
5.2	0.1040	0.1034	1	14.9
10.5	.2100	.2056	2	15.0
15.8	.3160	.3013	3	15.3
21.8	.4360	.3996	4	15.4
			Average	15.2

TABLE III

DATA FOR IDENTITY PERIOD ALONG *b* AXIS

Goniometer scale readings: 103° 50', 54° 00'

e, mm.	tan μ	sin μ	n	I, Å.
16	0.3200	0.3049	1	5.05

Though no more layer lines were obtained, this value of I checks exactly with values taken from a photograph using a flat film and stationary crystal, in which interferences corresponding to two layer lines were obtained, both values being 5.05 Å.

Thus the dimensions of the unit cell are calculated directly to be a = 15.20, b = 5.05 and c = 9.66 Å. (axial ratio 3.01 : 1 : 1.91) and, since the unit cell is orthorhombic, the volume of this cell is 15.20 × 5.05 × 9.66 Å.^{3} = 742 Å.^{3}

The density of the crystals was obtained by suspending them in a liquid of known density. The liquid used was petroleum ether. Although *l*-phenylaminoacetic acid is insoluble in petroleum ether within the limits of error of this determination, the precaution was taken to allow the petroleum ether to stand in contact with the *l*-phenylaminoacetic acid for several hours before the determination was started. The density so obtained is 1.30.

Then N, the number of molecules in the unit cell, is obtained from

$$N = \frac{(\text{volume of unit cell}) \times (\text{density})}{\dfrac{(\text{mass of H atom})}{(\text{molecular wt.})} \times (\text{Avogadro's number})}$$

$$N = \frac{5.05 \times 9.66 \times 15.2 \times 10^{-24} \times 1.30}{(151/1.008) \times 1.663 \times 10^{-24}} = 3.88$$

This is very nearly four, so that N, the number of molecules in the unit cell, is taken as four.

Thus it was shown that *l*-phenylaminoacetic acid is orthorhombic, and contains four molecules per unit cell. These considerations alone would narrow down the possible space groups to the following:[12] C_{2v}^1, C_{2v}^2, C_{2v}^3, C_{2v}^4, C_{2v}^5, C_{2v}^6, C_{2v}^7, C_{2v}^8, C_{2v}^9, C_{2v}^{10}, $\underset{\sim}{Q}^1$, $\underset{\sim}{Q}^2$, $\underset{\sim}{Q}^3$, $\underset{\sim}{Q}^4$, all of which are based on Bravais lattice Γ_0. In the C_{2v} space groups the *a* and *b* axes are interchangeable. Of these space groups, C_{2v}^1 and $\underset{\sim}{Q}^1$ are at once eliminated as they call for no abnormal spacings; in these results (see Tables IV, V and VI) it is seen that the 9.66 spacing appears only as the identity period

TABLE IV

INTERFERENCES ON EQUATOR LINE OF FIG. 1, *l*-PHENYLAMINOACETIC ACID. CRYSTAL ROTATED AROUND THE *c* AXIS (= 9.66 Å.)

In Col. 1 the following abbreviations are used: vs = very strong, s = strong, m = medium, f = faint, vf = very faint. In Col. 2, the arc measured is the distance on the film from a spot to the corresponding spot on the other side of the central beam. Θ is the angle between the central beam and the diffracted beam.

Intensity	Arc, mm.	Θ, radians	Θ, degrees	Θ/2	Sin Θ/2	*d*, Å.
vs	10.0	0.100	5° 44′	2° 52′	0.0500	15.4
f	20.3	.203	11° 40′	5° 50′	.1016	7.58
Broad and diffuse	30.0	.300	17° 10′	8° 35′	.1493	5.16
	31.4	.314	18° 00′	9° 00′	.1564	4.92
	32.5	.325	18° 40′	9° 20′	.1623	4.75
f	36.9	.369	21° 10′	10° 35′	.1837	4.19
vs	40.8	.408	23° 25′	11° 43′	.2031	3.79
vf	46.0	.460	26° 20′	13° 10′	.2278	3.38
	46.0	Using Cu K_β wave length				3.05
s	51.2	.512	29° 20′	14° 40′	.2532	3.04
vf	55.9	.559	32° 00′	16° 00′	.2756	2.80
	55.9	Using Cu K_β wave length				2.52
vs	62.0	.620	35° 30′	17° 45′	.3049	2.52
vf	83.2	.832	47° 40′	23° 50′	.4041	1.91

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[12] Astbury and Yardley, "Tabulated Data for the Examination of the 230 Space Groups by Homogeneous X-rays," *Phil. Trans. Roy. Soc. London*, **224A**, 221 (1926).

TABLE V

INTERFERENCES ON EQUATOR LINE FOR CRYSTAL ROTATED AROUND 15.2 AXIS (*a* OR *b*)

Intensity	Arc, mm.	θ, radians	θ, degrees	θ/2	Sin θ/2	*d*, Å.
s	33.2	0.332	19° 00′	9° 30′	0.1651	4.66

TABLE VI

INTERFERENCES ON EQUATOR LINE FOR CRYSTAL ROTATED AROUND 5.05 AXIS (*a* OR *b*)

Intensity	Arc, mm.	θ, radians	θ, degrees	θ/2	Sin θ/2	*d*, Å.
vs	10.2	0.102	5° 50′	2° 55′	0.0509	15.1
f	20.3	.203	11° 40′	5° 50′	.1016	7.58
vvf	25.6	.256	14° 40′	7° 20′	.1276	6.04
s, broad	33.0	.330	18° 54′	9° 27′	.1642	4.68
vf	39.5	.395	22° 40′	11′ 20′	.1965	3.92
f	36.8	.368	21° 4′	10° 32′	.1828	4.22
	36.8	Using Cu K_β wave length				3.80
vs	41.0	.410	23° 30′	11° 45′	.2036	3.79
vf	43.3	.433	24° 50′	12° 25′	.2150	3.58
vf	46.2	.462	26° 30′	13° 15′	.2292	3.36
	46.2	Using Cu K_β wave length				3.03
vs	51.0	.510	29° 10′	14° 35′	.2518	3.06
f	55.6	.556	31° 50′	15° 55′	.2742	2.81
	55.6	Using Cu K_β wave length				2.53
s	61.8	.618	33° 25′	17° 47′	.3054	2.52
vf	64.0	.640	36° 40′	18° 20′	.3145	2.45
vvf	67.4	.674	38° 36′	19° 18′	.3305	2.33
	67.4	Using Cu K_β wave length				2.10
vf	74.3	.743	42° 34′	21° 17′	.3630	2.12
vf	83.9	.839	48° 4′	24° 2′	.4073	1.89
f	90.0	.900	51° 34′	25° 47′	.4350	1.77

(Table I), not as true first order reflection, and again halved, as 4.84 (Table IX). The same is true also of the 5.05 spacing. Q^3 and Q^4 are eliminated readily since they call for the halving of {1 0 0} and {0 1 0}, while the 15.2 spacing appears very strongly in these results. Space group C_{2v}^2 calls for halving of {0 *k* *l*} if *l* is odd; this condition is fulfilled (Table VIII). C_{2v}^3 requires halving of {*h* 0 *l*} if *l* is odd; this is not true, and C_{2v}^3 is eliminated (Table VII). In C_{2v}^4 {*h* 0 *l*} is halved if *h* is odd; that this is true may be seen in Table VII. C_{2v}^5 calls for halving of {*h* 0 *l*} if *h* is odd, and halving of {0 *k* *l*} if *l* is odd. Tables VII and VIII show both of these conditions to be fulfilled, and since C_{2v}^2 calls for only the latter of these two, and C_{2v}^4 for only the former, these two are eliminated. C_{2v}^6 and C_{2v}^7 require that {*h* 0 *l*} be halved if $h + l$ is odd; Table VII shows that this is not the case, thus eliminating these two. In C_{2v}^8 {0 *k* *l*} must be halved if *k* is odd; Table VIII shows that this is not the case. C_{2v}^9 and C_{2v}^{10} call for halving of {0 *k* *l*} if $k + l$ is odd; that this is not the case is readily seen from Table VIII. This leaves only space groups C_{2v}^5 and Q^2. Q^2 calls for only one abnormal spacing, the halving of {0 0 1}.

That other abnormal spacings occur can be seen from Tables VII and VIII; these two tables also show remarkable agreement with the conditions required for space group C_{2v}^5. The conclusion is, therefore, that *l*-phenylaminoacetic acid belongs to space group C_{2v}^5, which by its purely geometric derivation demands four asymmetric molecules per unit cell.

TABLE VII

SPACE GROUP ASSIGNMENT

One of the conditions for space group C_{2v}^5 is that $\{h\ 0\ l\}$ must be halved if h is odd. This condition also applies to space group C_{6v}^9. In this table Col. 3 − means that the spacing indicated should not appear, + means that it should. The observed values are taken from the photograph for which the crystal was rotated about the 5.05 axis; calculated spacings based on a = 15.2, b = 5.05.

1 *h 0 l*	2 *d*	3	4 Observed spacing	5 Other possible planes
100	15.2	−	15.1	
200	7.60	+	7.58	
300	5.06	−		
400	3.80	+	3.79	
500	3.04	−	3.06	402, 203
600	2.53	+	2.52	
700	2.17	−	2.12?	
800	1.90	+	1.89	205, 801, 005
001	9.66	+		
002	4.83	+	[a]	
003	3.22	+		
004	2.42	+	2.44	
005	1.93	+	1.89	205, 801, 800
101	8.15	−		
102	4.61	−	4.68	
103	3.16	−		
104	2.39	−		
105	1.92	−	1.89	205, 801, 800, 005
201	5.94	+	6.04	
202	4.07	+	3.92[b]	
203	2.97	+	3.06	402
204	2.30	+	2.33[c]	
205	1.87	+	1.89	801, 800, 005
301	4.49	−		
302	3.50	−	3.58	401
303	2.71	−		
304	2.18	−	2.12	404?
305	1.80	−		
401	3.56	+	3.58	
402	2.99	+	3.06	203
403	2.46	+	2.45	601
404	2.04	+	2.12	
405	1.72	+		
501	2.90	−	3.06	203, 402
502	2.56	−	2.52	600
503	2.21	−		
504	1.89	−	1.89	205, 801, 800, 005
601	2.45	+	2.45	403
602	2.25	+		
603	1.98	+		
604	1.75	+	1.77	802
701	2.12	−	2.12	404?
702	1.99	−		
703	1.81	−		
801	1.87	+	1.89	205, 800, 005
802	1.78	+	1.77	604

[a] This is in a region where apparently several interferences lie close together, giving a broad diffuse spot. Using a smaller crystal of the *d*-form, sharper spots were obtained; one was found corresponding to d = 4.84 Å. [b] Very faint. [c] Possibly Cu K_β line from spacing 2.10 Å.

Wyckoff[13] gives the following as the coördinates of the four equivalent points in space group C_{2v}^5: (x, y, z), $(\bar{x}, \bar{y}, z + 1/2)$, $(x + 1/2, \bar{y}, z)$, $(1/2 - x, y, z + 1/2)$. A drawing of the unit cell is shown in Fig. 2. Since any point on the lattice may be chosen as the origin, a different origin has been selected for each of the four points in such a way that all four points fall in

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[13] Wyckoff, "Analytical Expression of the Results of the Theory of Space Groups," Carnegie Institution, Washington, 1922, p. 22.

TABLE VIII

SPACE GROUP ASSIGNMENT

A comparison of C_{2v}^5 and C_{2v}^9, based on whether $\{0\ k\ l\}$ is halved if l is odd or if $(k + l)$ is odd. As in Table VII − indicates that the interference should not appear, + indicates that it should appear. Measurements in Col. 5 were taken from the equator of the film for the crystal rotated about the 5.05 axis; calculated spacings based on a = 5.05, b = 15.2.

1 0 k l	2 d	3 C_{2v}^5	4 C_{2v}^9	5 Obs. spacing	6 Other possible planes	1 0 k l	2 d	3 C_{2v}^5	4 C_{2v}^9	5 Obs. spacing	6 Other possible planes
001	9.66	−	−			031	4.49	−	+		
010	15.2	+	−	15.1		032	3.50	+	−	3.58	
002	4.83	+	+	[a]		033	2.71	−	+		
003	3.22	−	−			034	2.18	+	−	2.12	070
004	2.42	+	+	2.45		035	1.80	−	+		
005	1.93	−	−			041	3.56	−	−	3.58	032
020	7.60	+	+	7.58		042	2.99	+	+	3.06	050
030	5.06	+	−			043	2.46	−	−	2.45	004
040	3.80	+	+	3.79		044	2.04	+	+		
050	3.04	+	−	3.06	042	045	1.72	−	−		
060	2.53	+	+	2.52	052	051	2.90	−	+	3.06	042, 050
070	2.17	+	−	2.12	034	052	2.56	+	−	2.52	060
080	1.90	+	+	1.89	054	053	2.21	−	+		
011	8.15	−	+			054	1.89	+	−	1.89	080
012	4.61	+	−	4.68		061	2.45	−	−	2.45	004
013	3.16	−	+			062	2.25	+	+		
014	2.39	+	−	2.33[b]	024	063	1.98	−	−		
015	1.92	−	+			064	1.75	+	+	1.77	082
021	5.94	−	−	6.04		071	2.12	−	+	2.12	034, 070
022	4.07	+	+			072	1.99	+	−		
023	2.97	−	−	3.06	042	073	1.81	−	+		
024	2.30	+	+	2.33[b]	014	081	1.87	−	−	1.89	054, 080
025	1.87	−	−	1.89	054, 080	082	1.78	+	+	1.77	064

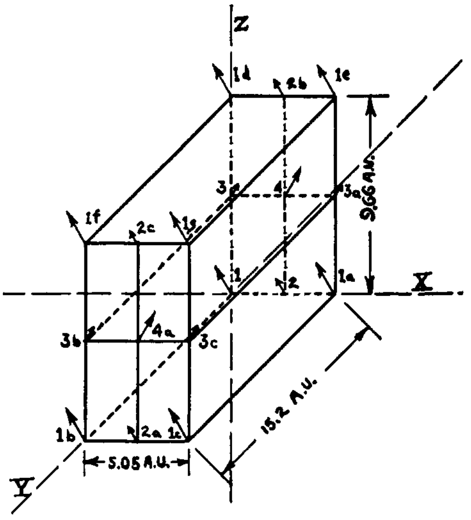
[a] See note *a* under Table VII. [b] See note *c* under Table VII.

the same unit parallelopiped. The other points that have the same relation to the lattice as these four are then placed. There are thus eight molecules at the eight corners of the cell. Since each of these is shared by eight unit parallelopipeds, one-eighth of these, or one, belongs to one unit cell. There are eight others that lie on edges of the parallelopiped. Each of these is shared by four unit parallelopipeds, whence one-fourth, or two, belong to the one unit cell. There are two more that lie in faces of the parallelopiped; since each of these is shared by two cells, one-half of these, or one, belongs to the one cell. Thus the total is four molecules per unit cell. It readily can be seen from the drawing that two of the spacings corresponding to the unit cell dimensions will be halved, while the third will not. As was observed above, the 9.66 and 5.05 Å. spacings did not appear except on the layer line diagrams, while the 15.2 Å. spacing was not halved. It may also be seen that the (0 1 0) planes are densely populated with molecules; this explains the high intensity of the reflections from these planes.

It is evident that the *c* axis (identity period 9.66 Å.) differs from the *a* and *b* axes in that it coincides with the dyad screw axis of symmetry.[12]

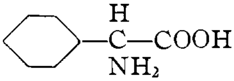
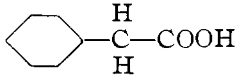
In explanation of Fig. 2, Arrow 1 is considered pointing behind the ZX plane and to the left of the YZ plane. Arrows 1 a, b, c, d, e, f and g are parallel to 1. Arrow 2 points in front of the ZX plane and to the left of a plane parallel to YZ. Arrows 2 a, b and c are parallel to 2. Arrow 3 points in front of the ZX plane and to the right of the YZ plane. Arrows 3 a, b and c are parallel to 3. Arrow 4 points behind the ZX plane and to the right of a plane parallel to YZ. 4a is parallel to 4. By a rotation of 180° and a translation of *c*/2, 1 will coincide with 3, 2 with 4, etc.

No attempt is made here to determine the orientation of the molecules within the unit cell other than the molecular asymmetry demanded by the space group, and the relative positions of the molecules as shown in the diagrams. To determine the relative positions of the atoms within any one molecule, and to determine just how these atoms are situated with respect to the axes requires careful measurement of the intensities of various reflections; even then many assumptions must be made. In this investigation it was considered that the intensity data were not sufficient and that the assumptions involved were not justifiable for the calculating of molecular sizes, shapes and orientations within the unit cell. Obviously the molecules must lie with their greatest length in the general direction of the *a* axis (15.2 Å.).



The four equivalent positions are shown at 1, 2, 3 and 4.

Fig. 2.—Diagram of the unit cell of active phenylaminoacetic acid, $C_6H_5CHNH_2COOH$.

It is of interest to compare the structure of active phenylaminoacetic acid  (I) with that of phenylacetic acid  (II), recently studied by Patterson.[14]

	I	II
Melting point, ° C.	248 or higher	76.5
System	Orthorhombic	Monoclinic

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[14] Patterson, *Phil. Mag.*, **3**, 1252 (1927).

	I	II
Space group	C_{2v}^5	C_{2h}^5 (b)
Molecules per unit cell	4	4
a	15.2	14.2
b	5.05	4.90
c	9.66	10.1
β	90°	101°
h k l halvings	*h* 0 *l*, *h* odd; 0 *k l*, *l* odd	0 1 0; *h* 0 *l*, *l* odd
Molecular symmetry	None	Center

The dimensions of the unit cells are remarkably similar and the comparison further verifies the correctness of the structure assigned. The presence of the basic amino and acid carboxyl groups in the same molecule affects profoundly the forces holding the molecule in the unit cell, as clearly shown by the inordinately high melting point. This is a further complication in interpretation of intensity data.

It is very important to note that the space group C_{2v}^5 admits of no possible molecular symmetry. Thus the classical theories of van't Hoff and Le Bel are confirmed, for here an examination has been made of an optically active substance, and the space group of the crystal requires that the molecule be asymmetric.

E. The Structure of *d*-Phenylaminoacetic Acid.—A rotation diagram of a crystal of this enantiomorph gave identically the same results as for the *l*-acid. For the rotation around the *b* (5.05 Å.) axis the 15.2 Å. spacing shows up strongly. It is interesting to note here that the 9.66 Å. spacing appears halved, as spacing 4.84 Å., while for the levo form there was no clearly defined interference. This is due to the fact that the crystal of dextro form used was smaller, and therefore the interferences were more distinct than on the film from the *l*-form, where the use of a larger crystal gave a more diffuse spot at the corresponding position. Powder photographs made with the General Electric X-Ray Diffraction apparatus, using the K_α radiation of molybdenum present further proof of the identity of the two active forms of phenylaminoacetic acid. It is thus quite clear

TABLE IX

MEASUREMENTS FOR *d*-PHENYLAMINOACETIC ACID

a = 50, *e* = 16, therefore *I* = 5.05 Å. (see Table III). Interferences on Equator Line.

Intensity	Arc, mm.	θ, radians	θ, degrees	θ/2	Sin θ/2	*d*, Å.
s	10.2	0.102	5° 50′	2° 55′	0.0509	15.1
f	32.0	.320	18° 20′	9° 10′	.1593	4.84
ms	33.0	.330	18° 54′	9° 27′	.1642	4.68
s	34.7	.347	19° 52′	9° 56′	.1725	4.46
f	35.8	.358	20° 30′	10° 15′	.1779	4.33
f	39.2	.392	22° 30′	11° 15′	.1951	3.94
vf	44.0	.440	25° 10′	12° 35′	.2179	3.54
f	57.0	.570	32° 40′	16° 20′	.2812	2.74
vf	68.1	.681	39° 00′	19° 30′	.3338	2.31

that the structure of *d*-phenylaminoacetic acid is the same as that of the *l*-form, and that these results show that X-ray diffraction methods offer no means of distinguishing between the two.

F. Study of the Racemic Modification.—A complete analysis of the crystalline structure of the racemic modification of phenylaminoacetic acid will be presented in another paper. However, ample proof is at hand that it differs from the active forms. In the powder spectra it can be readily seen that there is no correspondence of diffraction lines between active and racemic forms. A rotating crystal photograph of the racemic form was made using the same apparatus as described above. The identity period calculated from this photograph is 4.26 Å., differing widely from any observed in the case of the active form. This evidence is sufficient to prove that the racemic form has a different crystalline structure than the active forms.

Summary

1. An x-ray examination by the rotation and powder diffraction methods has been made of the *d*-, *l*- and racemic forms of phenylaminoacetic acid. The power of the rotation method is shown by the fact that a straightforward crystal structure analysis was possible although no crystallographic or optical data were available.

2. The *d*- and *l*- forms are shown to crystallize in the orthorhombic system, upon Bravais lattice Γ_0, space group C_{2v}^5. The unit cell containing four molecules has the dimensions $a = 15.2$, $b = 5.05$, $c = 9.66$ Å.

3. The fact that space group C_{2v}^5 admits of no molecular symmetry confirms the classical theories of van't Hoff and Le Bel connecting molecular asymmetry with optical activity.

4. It has not been found possible to distinguish between the *d*- and *l*-forms by means of x-ray diffraction methods.

5. The crystal form of the racemic modification differs from that of the optically active forms.

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