

## An X-Ray Crystallographic Study of Some Racemates and Quasi-racemates

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Unit cells and space groups of some racemates and quasi-racemates have been determined. The following data were found: Quasi-racemate of (-)-1,2-dithiane-3,6-dicarboxylic acid and (+)-1,2-diselenane-3,6-dicarboxylic acid,  $a = 9.75 \text{ \AA}$ ,  $b = 9.38 \text{ \AA}$ ,  $c = 9.80 \text{ \AA}$ ,  $\beta = 103 \frac{1}{2}^\circ$ ; space group  $C_2^3 - I2$  with  $Z = 4$ . *Racem-a*-(1-naphthyl)-propionic acid,  $a = 7.89 \text{ \AA}$ ,  $b = 9.04 \text{ \AA}$ ,  $c = 15.01 \text{ \AA}$ ,  $\beta = 96 \frac{1}{2}^\circ$ ; space group  $C_{2h}^5 - P2_1/c$  with  $Z^* = 4$ . *Racem-a*-(3-thianaphthenyl)-propionic acid,  $a = 8.71 \text{ \AA}$ ,  $b = 10.45 \text{ \AA}$ ,  $c = 11.01 \text{ \AA}$ ,  $\beta = 96^\circ$ ; space group  $C_{2h}^5 - P2_1/c$  with  $Z = 4$ . Quasi-racemate of *a*-(1-naphthyl)-propionic acid and *a*-(3-thianaphthenyl)-propionic acid,  $a = 8.86 \text{ \AA}$ ,  $b = 29.00 \text{ \AA}$ ,  $c = 8.07 \text{ \AA}$ ,  $Z = 8$ , space group probably  $D_2^4 - P2_12_12_1$ . *Racem-a*-(3-indolyl)-propionic acid,  $a = 16.00 \text{ \AA}$ ,  $c = 7.79 \text{ \AA}$ ; space group  $C_{4h}^4 - P4_2/n$  with  $Z = 8$ .

The unit cell and space group of the quasi-racemate of dithiane-dicarboxylic acid and diselenane-dicarboxylic acid are closely related to those of the parent, true racemates, the major difference being the lack of the centre of symmetry and the glide planes which transform one antipode into the other. The similarity in structure has been confirmed through Fourier analysis of the  $b$ -axis projection of this quasi-racemate. The result is in agreement with views concerning the constitution of quasi-racemates put forward by Fredga and Hägg. No corresponding relation seems to exist between the structure of the other quasi-racemate and those of the parent, true racemates.

About sixty years ago, racemate-like compounds showing optical activity were reported by Centnerzwer<sup>1</sup>. During the last 20-30 years especially Fredga and co-workers have made comprehensive studies of such compounds, which by Fredga were termed quasi-racemates<sup>2,3</sup>.

A quasi-racemate can be derived from a corresponding, true racemate by a not too extensive change in one of the antipodes<sup>3,4</sup>. True antipodes can be brought to coincide by means of the symmetry elements  $\bar{1}, m, c$  and  $\bar{4}$ . In a quasi-racemate, the components are not true enantiomorphs; by means of the

above-mentioned symmetry elements they can be brought to coincide approximately<sup>2</sup>, but not exactly, because at least one atom or atom group is different in the two molecules. If the lack of these symmetry elements is the only difference from the space group of a parent racemate, there will, as pointed out by Hägg<sup>5</sup>, be a simple relation between the space groups of the two. Where this rule is valid and the cell dimensions are similar, the (+) and (−) components in racemate and quasi-racemate will probably be distributed on roughly the same positions. The only possibility for all symmetry elements of a true racemate to remain in a quasi-racemate would be through a statistical distribution of the molecules.

## CRYSTAL DATA

Unit cell and space group data were obtained from single-crystal oscillation and Weissenberg photographs. CuK $\alpha$  radiation with  $\lambda = 1.542 \text{ \AA}$  was used. Axial lengths are believed to be accurate within  $\pm 0.5 \%$ . Densities were determined by a flotation method.

*Quasi-racemate of (−)-1,2-dithiane-3,6-dicarboxylic acid and (+)-1,2-diselenane-3,6-dicarboxylic acid (III)*<sup>6</sup>. For comparison with the parent racemates, *racem-1,2-dithiane-3,6-dicarboxylic acid (I)*<sup>6-8</sup> and *racem-1,2-diselenane-3,6-dicarboxylic acid (II)*<sup>6,7,9</sup>, the unit cell and space group data of all three are listed below:

	<i>C</i> -centered setting		<i>I</i> -centered setting		<i>b</i>	<i>c</i>	<i>Z</i>	Space group
	<i>a</i>	$\beta$	<i>a</i>	$\beta$				
I	12.09 Å	129°	9.62 Å	102 ½°	9.26 Å	9.70 Å	4	$C_{2h}^6-2/c$
II	9.97 Å	105°	12.01 Å	127°	9.43 Å	9.78 Å	4	$C_{2h}^6-2/c$
III	12.11 Å	128 ½°	9.75 Å	103 ½°	9.38 Å	9.80 Å	4	$C_2^3-2$

The most orthogonal cells have been chosen for further work. The crystals of III were yellow prisms, monoclinic sphenoidic, with density, calc. 1.94, found 1.96 g/cm<sup>3</sup>. There are two molecules of each type in the unit cell.

*Racem-a-(1-naphthyl)-propionic acid (IV)*. Flat colourless prisms, monoclinic prismatic, extended along the *b*-axis with forms {100} and apparently {001}, {110} and {011} were developed on some crystals. There are four molecules in a unit cell of dimensions  $a = 7.89 \text{ \AA}$ ,  $b = 9.04 \text{ \AA}$ ,  $c = 15.01 \text{ \AA}$ , and  $\beta = 96\frac{1}{2}^\circ$ . Density, calc. and found 1.25 g/cm<sup>3</sup>. Systematic absences,  $h0l$  when  $l$  is odd and  $0k0$  when  $k$  is odd. The space group is then  $C_{2h}^5-P2_1c$ .

*Racem-a-(3-thianaphthenyl)-propionic acid (V)*. Large irregular crystals with  $a = 8.71 \text{ \AA}$ ,  $b = 10.45 \text{ \AA}$ ,  $c = 11.01 \text{ \AA}$ , and  $\beta = 96^\circ$ . There are four molecules in a unit cell; density, calc. 1.37, found 1.34 g/cm<sup>3</sup>. Systematic absences are  $0k0$  when  $k$  is odd and  $h0l$  when  $l$  is odd. The space group is thus  $C_2^5-P2_1c$ .

*Quasi-racemate of a-(1-naphthyl)-propionic acid and a-(3-thianaphthenyl)-propionic acid. (VI)*. Irregular prisms and needles elongated along the *c*-

axis, bounded by  $\{110\}$  and, less developed,  $\{010\}$ ;  $\{011\}$  was seen on some crystals. Unit cell data are,  $a = 8.86 \text{ \AA}$ ,  $b = 29.00 \text{ \AA}$ , and  $c = 8.07 \text{ \AA}$ . 4 molecules of each kind per unit cell. Density, calc. 1.30, found 1.29 g/cm<sup>3</sup>. Systematic absences,  $h00$  when  $h$  is odd,  $0k0$  when  $k$  is odd. Even after long exposure, no  $00l$  reflections could be observed. Possible space groups:  $D_2^3-P2_12_12_1$  or  $D_2^3-P2_12_12$ .

Racem-*a*-(3-indolyl)-propionic acid (VII). Small orange needles and prisms extended along the *c*-axis, bounded by  $\{110\}$  and  $\{001\}$ . From the symmetry of the photographs, the crystals are tetragonal. Unit cell data were  $a = 16.00 \text{ \AA}$ ,  $c = 7.79 \text{ \AA}$ . Density, calc. 1.26, found 1.24 g/cm<sup>3</sup>. Systematic absences are  $hk0$  when  $h + k$  are odd, and  $00l$  when  $l$  is odd. The space group is therefore  $C_{4h}^4-P4_2/n$ .

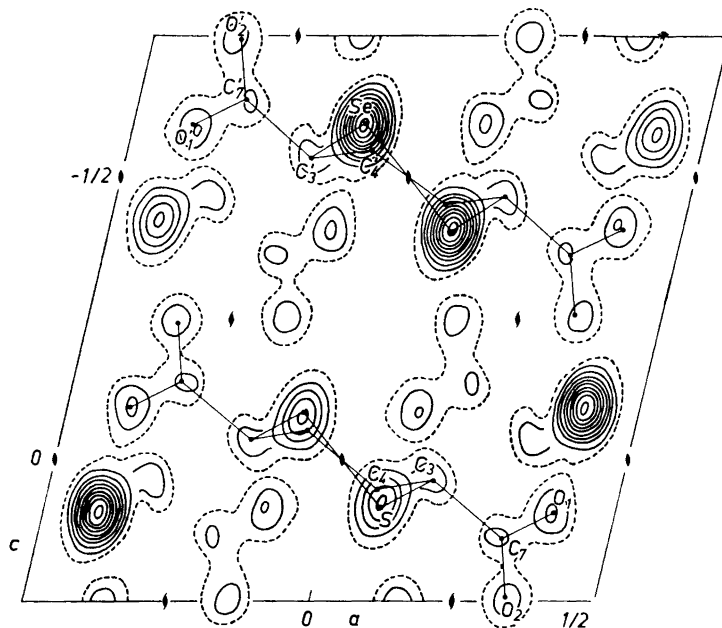
It appears that the true racemates crystallize in non-enantiomorphous space groups. This is not the case with the space groups of the two quasi-racemates, which are lacking the symmetry elements  $\bar{1}, m, c$  and  $\bar{4}$ ; one or more of which are found in true racemates. The unit cells of I, II and III are very similar; this is not unexpected because of the small difference in covalent radius between sulphur and selenium. The quasi-racemate III does not possess the glide planes and symmetry centres of I and II. As this is the only difference between their space groups, the rule of Hägg<sup>5</sup> is valid here, and the positions in the crystal lattice of III should be occupied in the same manner as in I and II.

The racemates IV and V are not isomorphous, nor is there any relation between the unit cell and space group of any of these and that of the corresponding quasi-racemate VI. This must be the result of the relatively great structural difference between the components of the quasi-racemate, which apparently require quite another packing of the molecules than in the parent, true racemates.

To confirm the similar arrangement in III and its parent, true racemates, the projection of the structure of III along the *b*-axis was worked out. The detailed crystal structures of I<sup>8</sup> and II<sup>9</sup> have already been determined in this laboratory.

#### A FOURIER ANALYSIS OF THE QUASI-RACEMATE OF (-)-1,2-DITHIANE-3,6-DICARBOXYLIC ACID AND (+)-1,2-DISELENANE-3,6-DICARBOXYLIC ACID

The intensities of the  $h0l$  reflections were estimated visually from zero layer Weissenberg photographs. Ni-filtered CuK radiation with  $\lambda = 1.542 \text{ \AA}$  was used. 90 out of 117 reflections within the range of  $\sin \theta = 0.980$  were observed and measured. The intensities were corrected for Lorentz and polarization factors. They were then converted to relative structure amplitudes and ultimately brought to an approximately absolute scale by comparison with the calculated values. Because of the similarity in cell dimensions and the simple relation between the space groups of I, II and III, the atomic positions were assumed to be little different in the three compounds. In the true racemates I<sup>8</sup> and II<sup>9</sup>, with space group<sup>7</sup>  $C_{2h}^6-2/c$ , the systematic absences of  $h0l$  when  $h$  is odd and  $l$  is odd, are caused by the axial and diagonal glide



*Fig. 1.* Electron density projection of the quasi-racemate of (–)-1,2-dithiane-3,6-dicarboxylic acid and (+)-1,2-diselenane-3,6-dicarboxylic acid along the *b*-axis. One unit cell (four asymmetric units) are shown. Lines are drawn to indicate one molecule of each kind. The contour intervals are  $5 \text{ e}/\text{\AA}^2$  for sulphur and selenium,  $3 \text{ e}/\text{\AA}^2$  for oxygen and carbon, and the 5-electron line is dashed.

planes. These glide planes do not exist in III, but are replaced by pseudo glide planes, which transform a dithiane-dicarboxylic acid molecule into a diselenane-dicarboxylic acid molecule. This will as observed on the photographs, cause the  $h0l$  reflections with odd indices to be weak and the other reflections to be intermediates between the corresponding ones in I and II. The assumption was therefore made, that where corresponding reflections with both  $h$  and  $l$  even had the same sign in I and II, they probably had that sign in III too. In this way, signs of 30 relatively strong reflections were found. The resulting Fourier map showed a clear resemblance to the  $h0l$  maps from I<sup>8</sup> and II<sup>9</sup>, with an asymmetric unit of half the real one and a well resolved average S-Se peak and peaks for the lighter atoms. Sulphur and selenium were then placed in the real asymmetric unit in positions corresponding to the heavy atoms in (+) and (–) molecules in I<sup>8</sup>, with twofold axes in the middle of the rings. With the heavy atoms placed, the structure was solved and refined through successive Fourier and difference syntheses.

Beevers-Lipson strips were used for summation at intervals of  $6^\circ$ . The atomic coordinates from the final structure factor calculation were corrected for gradients still present in several atomic positions in the last difference map.  $C_4$  and  $C_4'$  overlap with sulphur and selenium and were placed so as to obtain

C-C bonds of 1.54 Å. The final coordinates for half a molecule of each type are listed in Table 1, and indicated through dots in the final electron density map in Fig. 1. A prime is used to denote the lighter atoms in the diselenane-dicarboxylic acid molecule. For comparison, the final atomic coordinates of I<sup>8</sup> and II<sup>9</sup> are also listed in Table 1.

The observed and calculated structure factors are listed in Table 2. Atomic scattering curves used were those of Viervoll and Øgrim<sup>10</sup> for sulphur, of Berghuis *et al.*<sup>11</sup> for carbon and oxygen and of Thomas and Umeda<sup>12</sup> for selenium. The Se-curve was corrected for dispersion and anomalous diffraction<sup>13,14</sup>. In the temperature factors,  $\exp[-B(\sin^2\theta/\lambda^2)]$ , used in calculation of structure factors, the final values of  $B$ , chosen on basis of the difference maps, were 4.0 Å<sup>2</sup> and 5.0 Å<sup>2</sup> for carbon and oxygen, respectively, and  $(2 + 6\cos^2\varphi)$  Å<sup>2</sup> for sulphur and  $(2.5 + 4\cos^2\varphi)$  Å<sup>2</sup> for selenium, where  $\varphi$  is the angle between the normal of the reflecting plane and the direction of maximum vibration of the atoms. The latter direction made an angle of 15° with the  $c$ -axis in the acute angle in both cases.

Table 1. Atomic coordinates of the quasi-racemate III in fractions of cell edges. Origin on twofold axis in the dithiane-dicarboxylic acid molecule.

The dithiane-dicarboxylic acid molecule			The diselenane-dicarboxylic acid molecule		
	$x$	$z$		$x$	$z$
S	0.0871	0.0846	Se	0.4030	-0.0957
C <sub>3</sub>	0.168	0.036	C <sub>3</sub> '	0.323	-0.034
C <sub>4</sub>	0.073	0.052	C <sub>4</sub> '	0.425	-0.047
C <sub>7</sub>	0.312	0.139	C <sub>7</sub> '	0.186	-0.137
O <sub>1</sub>	0.391	0.094	O <sub>1</sub> '	0.104	-0.092
O <sub>2</sub>	0.342	0.246	O <sub>2</sub> '	0.153	-0.243

Atomic coordinates of corresponding molecules in the true racemates I<sup>9</sup> and II<sup>9</sup>, respectively, in fractions of cell edges.

<i>Racem</i> -dithiane-dicarboxylic acid			<i>Racem</i> -diselenane-dicarboxylic acid		
	$x$	$z$		$x$	$z$
S	0.0885	0.0825	Se	0.3976	-0.0896
C <sub>3</sub>	0.171	0.042	C <sub>3</sub>	0.330	-0.037
C <sub>4</sub>	0.072	0.052	C <sub>4</sub>	0.428	-0.045
C <sub>7</sub>	0.313	0.129	C <sub>7</sub>	0.188	-0.125
O <sub>1</sub>	0.396	0.092	O <sub>1</sub>	0.090	-0.092
O <sub>2</sub>	0.348	0.248	O <sub>2</sub>	0.171	-0.248

The relatively strong reflection 10 $\bar{1}$ , has markedly lower observed than calculated value, probably due to secondary extinction, and was therefore omitted from the difference syntheses and scale factor calculation, and included in the final Fourier synthesis with calculated instead of observed value. The final reliability index  $R = \Sigma||F_o| - |F_c|| / \Sigma|F_o|$  with non-observed reflections included when  $|F_c|$  exceeded the observable limit, and 10 $\bar{1}$  excluded, was 0.086.

Table 2. Observed and calculated  $h0l$  structure factors for the quasi-racemate of (-)-1,2-dithiane-3,6-dicarboxylic acid and (+)-1,2-diselenane-3,6-dicarboxylic acid.

$h$	$F_o$	$F_c$	$h$	$F_o$	$F_c$
	$h00$			$h04$	
2	41	29	0	62	- 63
4	160	- 160	2	108	- 110
6	67	- 67	4	7	1
8	15	- 12	6	59	54
10	43	40	8	26	28
	$h01$		10	11	- 9
1	14	- 16		$h0\bar{4}$	
3	50	53	2	48	54
5	31	32	4	61	63
7	18	- 16	6	50	55
9	27	- 23	8	30	- 29
11	< 4	- 1	10	55	- 47
	$h0\bar{1}$		12	< 5	3
1	48	- 63		$h05$	
3	15	- 16	1	28	29
5	35	37	3	16	- 16
7	28	26	5	30	- 30
9	14	- 12	7	< 8	- 2
11	16	- 15	9	13	16
	$h02$			$h0\bar{5}$	
0	97	94	1	30	33
2	46	- 37	3	13	- 9
4	118	- 112	5	28	- 31
6	35	- 25	7	< 8	- 3
8	42	41	9	15	13
10	36	33	11	< 6	5
	$h0\bar{2}$			$h06$	
2	120	130	0	82	- 93
4	50	55	2	32	- 31
6	72	- 74	4	65	66
8	55	- 54	6	26	27
10	< 8	4	8	12	- 11
12	16	18		$h0\bar{6}$	
	$h03$		2	14	- 15
1	44	48	4	40	44
3	34	34	6	53	53
5	18	- 17	8	< 8	- 1
7	31	- 27	10	29	- 22
9	< 7	- 3		$h07$	
	$h0\bar{3}$		1	11	- 11
1	13	- 16	3	23	- 24
3	41	- 48	5	< 8	3
5	12	- 13	7	13	15
7	23	24			
9	20	15			
11	8	- 7			

$h$	$F_o$	$F_c$	$h$	$F_o$	$F_c$
	$h0\bar{7}$			$h010$	
1	17	19	0	< 7	4
3	19	20	2	14	14
5	< 8	- 7	4	< 5	- 5
7	15	- 13			
9	< 7	- 1			
11	5	4			
	$h08$			$h0\bar{1}\bar{0}$	
0	< 8	4	2	< 8	4
2	< 8	6	4	12	- 9
4	16	18	6	17	- 15
6	9	2	8	10	11
	$h0\bar{8}$			$h011$	
2	26	- 23	1	< 6	- 1
4	19	- 18	3	< 4	6
6	17	18			
8	20	16		$h0\bar{1}\bar{1}$	
10	< 6	0	1	8	- 9
	$h09$		3	< 7	- 2
1	14	- 14	5	< 6	4
3	< 7	- 3	7	< 5	2
5	8	11			
	$h0\bar{9}$			$h012$	
1	< 8	- 6	0	< 4	3
3	11	10			
5	11	8		$h0\bar{1}\bar{2}$	
7	< 7	- 3	2	8	8
9	7	- 4	4	6	- 8
			6	< 4	- 4

The standard deviation of the electron density is  $0.53 e/\text{\AA}^2$ , estimated from the last difference map. The s. d. of the atomic coordinates were found from the root-mean-square gradients of the same map and the curvatures of the peaks in the final Fourier map<sup>15</sup>. For overlapped atoms, the standard deviations were taken as about twice those which would otherwise have applied. The following values were found:  $\sigma(x) = 0.007 \text{\AA}$ ,  $\sigma(z) = 0.009 \text{\AA}$  for S;  $\sigma(x) = 0.003 \text{\AA}$ ,  $\sigma(z) = 0.004 \text{\AA}$  for Se. For the other atoms, the s. d. varied between 0.02 and  $0.07 \text{\AA}$ .

STRUCTURE OF THE QUASI-RACEMATE OF (-)-1,2-DITHIANE-3,6-DICARBOXYLIC ACID AND (+)-1,2-DISELENANE-3,6-DICARBOXYLIC ACID AS COMPARED WITH THE CORRESPONDING TRUE RACEMATES

With only one projection, the true distances which can be calculated are those over twofold axes and screw axes. These distances together with some of the corresponding distances of the parent racemates<sup>8,9</sup> are listed in Table 3 below.

The S-S and the Se-Se bond lengths show good agreement in the three compounds. As the atoms also have approximately the same  $x$  and  $z$  coordinates in I, II and III, as shown in Table 1, it is clear that the constitution of

this quasi-racemate and its parent racemates is very similar. The unit cells of I and III are very like, both having *I*-centered settings with twofold screw axes and twofold axes in the same positions. As seen from Table 3, some distances across these axes show good agreement.

Table 3. Bond lengths in Å.

	I	II	III
S-S	2.069 ± 0.014		2.078 ± 0.016
Se-Se		2.321 ± 0.012	2.332 ± 0.007
C <sub>4</sub> -C <sub>5</sub>			1.55 ± 0.13
C <sub>4</sub> '-C <sub>5</sub> '			1.54 ± 0.12

Non-bonded intermolecular distances in Å.			
Shortest distances over twofold screw axes		Shortest distances over twofold axes	
S-S in I	6.12	O <sub>1</sub> -O <sub>1</sub> in I	2.94
S-S in III	6.15	O <sub>1</sub> '-O <sub>1</sub> ' in III	3.12
Se-Se in III	5.99	O <sub>1</sub> '-O <sub>1</sub> ' in III	3.01

In the *C*-centered racemate II, the packing of the molecules is a little different from that in the *I*-centered I and III, there being an interchange of locations of screw axes and symmetry centres at  $x = 1/4$  and  $x = 3/4$ . This allows a closer non-bonded approach of the selenium atoms in II and is also reflected in the orientation of the carboxyl group, which is different in II as compared with I and III. The difference in packing is probably caused by the difference in van der Waals radius between sulphur and selenium, together with a tendency of minimum distance between heavy atoms<sup>9</sup>.

The *b*-axis projection of the structure of this quasi-racemate thus confirms the conclusions from space group data that the (+) and (-) molecules are distributed on the same positions as in the parent, true racemates.

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