The Crystal and Molecular Structure of a Brominated Compound Derived from Paeoniflorin

By Miyuki Kaneda and Yoichi Iitaka

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

The crystal structure of the brominated compound, $C_{35}H_{39}O_{15}Br$, has been determined in order to confirm the molecular structure and to determine the absolute configuration of paeoniflorin, $C_{23}H_{28}O_{11}$, a monoterpene glucoside isolated from *Paeonia albiflora* Pallas. The crystals are orthorhombic with space group $P2_12_12_1$ and the unit cell dimensions are $a = 13\cdot58$, $b = 21\cdot74$, $c = 12\cdot61$ Å; $Z = 4$. The crystal structure was solved by the heavy atom method and refined by the block-matrix least-squares method. The final R value for 1844 observed reflexions was $0\cdot107$. The molecular structure of paeoniflorin deduced from the present X-ray study of the brominated compound was in complete agreement with the proposed structure, a novel glucoside of a monoterpene of the pinane group. The absolute configuration was determined by the use of the anomalous dispersion effect of the bromine atom for Cu $K\alpha$ radiation, which is compatible with the fact that the glucosidic residue is of D-glucose.

Introduction

Paeoniflorin (Fig. 1,I), $C_{23}H_{28}O_{11}$, was first isolated from *Paeonia albiflora* Pallas by Shibata & Nakahara (1963). Subsequently, the chemical structure was proposed as (I) except for the absolute configuration on the basis of chemical and spectroscopic data (Shibata, Nakahara & Aimi, 1963; Shibata, Nakahara & Aimi, 1964; Aimi, Inaba, Watanabe & Shibata, 1969). It is a unique type monoterpene glucoside whose basic skeleton consists of a cage-like pinane derivative. To date only the iridoid and cyclocitral type monoterpene glycosides have been found in nature. Of these, only two iridoid glycosides have been investigated by X-ray diffraction methods (Masaki, Hirabayashi, Fuji, Osaki & Inouye, 1967; Lentz & Rossmann, 1969).

In view of the uniqueness of the structure, an X-ray structure determination of paeoniflorin was attempted to confirm the molecular structure and to elucidate the exact stereochemistry including its absolute configuration. However, any simple heavy atom derivatives of paeoniflorin failed to yield a suitable crystal for X-ray analysis. Only the crystal of a brominated compound (Fig. 1, V) of one of the ethanolysis products of paeoniflorin was at last found to be suitable. Although the original hemiketal linkage was broken during the ethanolysis reaction, the structure of the derived compound could easily be correlated to that of paeoniflorin by taking into account the reaction mechanism of the ethanolysis. We therefore decided to carry out the X-ray analysis on this brominated compound (V).

Experimental

Treatment of paeoniflorin (I) with *p*-toluenesulphonic acid (TsOH) in ethanol, afforded two kinds of ethyl ether, product K_1(II) and product K_2(III). Bromination of product K_2-acetate (IV) by treatment with bromine in chloroform solution gave a suitable heavy atom derivative (V), $C_{33}H_{39}O_{15}Br$, for X-ray analysis.

The crystals of (V), grown from methanol solution, were colourless plates elongated along the c axis. The density was measured by the flotation method in a mixture of hexane and carbon tetrachloride. The cell dimensions and space group were determined from precession photographs taken with Cu $K\alpha$ radiation.

Crystal data

Bromo-derivative of paeoniflorin, $C_{33}H_{39}O_{15}Br$, M. W. 755, m.p. 199–200°.
$[\alpha]_D^{18} = -7\cdot3°$
Orthorhombic
$a = 13\cdot59 \pm 0\cdot02$, $b = 21\cdot74 \pm 0\cdot04$, $c = 12\cdot61 \pm 0\cdot01$ Å
$U = 3727$ Å^3
$D_m = 1\cdot354$, $D_x = 1\cdot352$ g.cm^{-3}, $Z = 4$
$F(000) = 1568$.
Absent reflexions: $h00$ when h is odd, $0k0$ when k is odd, and $00l$ when l is odd.
Space group: $P2_12_12_1$.
Linear absorption coefficient for Cu $K\alpha$ radiation: $\mu = 22\cdot6$ cm^{-1}.

Three-dimensional intensity data were collected from equi-inclination Weissenberg photographs. The layers $hk0 \sim hk8$ about the c axis and $0kl \sim 4kl$ about the a axis were taken with Cu $K\alpha$ radiation using the multiple-film technique. The intensities of several thousands of reflexions were measured by photodensitometer. The reflexions which were too weak to be measured were not included in the present determination. The specimens used for the intensity measurement were about $0\cdot13 \times 0\cdot11 \times 0\cdot40$ mm in size for the c axis and $0\cdot40 \times 0\cdot50 \times 0\cdot40$ mm for the a axis Weissenberg photographs. Since the μR values never exceed $0\cdot86$ in all cases, no absorption correction was applied for the intensity data. The spot-shape correction was made by taking a mean intensity value of the elongated and contracted spots for each reflexion. All the intensity

data were then corrected for Lorentz and polarization factors and were put on a common scale by correlation of the structure factors on various layers. 1844 independent structure factors were finally derived.

Determination of the structure

The structure was solved by the heavy atom method. A sharpened Patterson synthesis was computed with the structure factor values corresponding to atoms at rest. From the three Harker sections, the coordinates of the bromine atom were found to be $x = 0.135$, $y = 0.120$, $z = 0.0$. A three-dimensional electron density distribution map calculated by use of the bromine phase angles showed pseudo-mirror planes on (001) at $z = 0$, $\frac{1}{2}$, etc. Until the fourth Fourier synthesis, thirty-eight atoms were sorted out from their mirror images. Refinement of the positional parameters of the thirty eight atoms was carried out by the block-matrix least-squares method. Five cycles of calculation in which only the anisotropic thermal vibrations of the bromine atom were allowed for, gave an R value of 0.30.

Table 1. *Final atomic parameters and their standard deviations* ($\times 10^4$)

Temperature factors are of the form

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

The e.s.d.'s are given in parentheses in units of the least significant digits.

To represent the correct absolute configuration, the following coordinates should be referred to the left-handed coordinate system.

	x	y	z	β_{11}	β_{22}	β_{33}	β_{12}	β_{13}	β_{23}
Br	1356 (3)	1184 (1)	−94 (2)	197 (4)	29 (1)	82 (2)	−14 (1)	9 (3)	16 (1)
C(1)	637 (12)	8 (8)	1887 (12)	14 (10)	22 (4)	40 (10)	3 (6)	10 (9)	0 (6)
C(2)	176 (13)	183 (7)	835 (12)	35 (11)	15 (4)	37 (9)	5 (6)	−2 (9)	−5 (5)
C(3)	1002 (15)	320 (8)	41 (13)	73 (14)	19 (4)	43 (10)	−5 (7)	13 (12)	8 (6)
C(4)	1924 (15)	−34 (10)	185 (16)	44 (14)	35 (6)	60 (14)	−14 (8)	4 (12)	−7 (8)
C(5)	1998 (14)	−321 (9)	1261 (14)	38 (13)	30 (5)	44 (11)	−7 (7)	14 (11)	0 (6)
C(6)	1015 (14)	−658 (8)	1598 (13)	41 (12)	21 (4)	40 (10)	2 (6)	2 (11)	−5 (5)
C(7)	1717 (14)	237 (9)	2053 (15)	30 (13)	31 (5)	59 (13)	2 (7)	−1 (11)	−10 (7)
C(8)	1183 (17)	−1099 (10)	2570 (16)	69 (16)	28 (5)	71 (14)	7 (8)	6 (14)	4 (7)
C(9)	346 (17)	−872 (9)	722 (14)	74 (16)	26 (5)	45 (12)	0 (8)	−5 (13)	−5 (6)
C(10)	−677 (16)	669 (10)	921 (15)	56 (14)	33 (5)	55 (13)	17 (8)	−5 (13)	2 (7)
C(11)	256 (14)	372 (9)	3665 (13)	36 (12)	28 (5)	40 (11)	−3 (7)	5 (11)	−2 (6)
C(12)	−475 (15)	207 (9)	4528 (14)	46 (13)	26 (5)	46 (11)	1 (7)	−1 (11)	3 (6)
C(13)	−220 (13)	615 (8)	5500 (13)	34 (11)	22 (4)	34 (10)	−6 (6)	8 (10)	1 (5)
C(14)	−112 (13)	1282 (7)	5172 (12)	36 (12)	18 (4)	38 (10)	−4 (6)	0 (10)	−5 (5)
C(15)	548 (15)	1350 (8)	4257 (14)	45 (13)	24 (5)	46 (11)	1 (7)	6 (11)	1 (6)
C(16)	565 (16)	2024 (9)	3873 (16)	69 (16)	26 (5)	57 (13)	7 (8)	16 (13)	1 (7)
C(17)	1749 (17)	−2141 (10)	2691 (16)	70 (16)	28 (5)	63 (14)	−2 (8)	3 (13)	5 (7)
C(18)	2082 (15)	−2654 (9)	2108 (19)	24 (13)	25 (5)	117 (19)	2 (7)	−20 (13)	6 (8)
C(19)	2334 (16)	−2655 (9)	1024 (17)	45 (15)	25 (5)	85 (16)	−5 (7)	−6 (14)	−4 (8)
C(20)	2671 (19)	−3154 (11)	469 (20)	68 (18)	33 (6)	116 (20)	−4 (9)	−8 (17)	−8 (10)
C(21)	2832 (17)	−3709 (10)	1114 (18)	59 (16)	30 (6)	93 (16)	3 (8)	−1 (15)	1 (8)
C(22)	2654 (18)	−3729 (11)	2136 (20)	54 (17)	29 (6)	131 (21)	7 (9)	−1 (16)	2 (10)
C(23)	2314 (18)	−3206 (10)	2717 (18)	72 (17)	24 (5)	97 (17)	−5 (8)	13 (15)	16 (8)
C(24)	394 (19)	−1237 (11)	−1062 (19)	83 (18)	36 (7)	91 (18)	−10 (10)	−5 (17)	−21 (10)
C(25)	1229 (21)	−1285 (11)	−1952 (19)	101 (21)	41 (7)	77 (17)	−6 (11)	21 (18)	−28 (9)
C(26)	−938 (10)	−847 (11)	5014 (18)	86 (18)	31 (6)	77 (16)	1 (9)	12 (17)	6 (9)
C(27)	−517 (20)	−1460 (13)	5272 (22)	77 (20)	37 (7)	124 (23)	−13 (10)	−20 (19)	10 (11)
C(28)	−790 (18)	414 (11)	7267 (18)	94 (18)	28 (6)	64 (15)	4 (9)	31 (15)	−6 (8)
C(29)	−1905 (25)	473 (15)	7867 (23)	163 (30)	54 (10)	96 (23)	−24 (15)	64 (23)	−6 (13)
C(30)	−174 (16)	1961 (9)	6707 (15)	71 (15)	23 (4)	53 (12)	4 (8)	−2 (13)	−9 (6)
C(31)	367 (20)	2198 (14)	7595 (18)	94 (21)	58 (9)	54 (14)	−2 (12)	−12 (17)	−3 (10)
C(32)	1454 (19)	2596 (9)	2533 (17)	84 (17)	25 (5)	69 (15)	1 (8)	1 (15)	−0 (7)
C(33)	2216 (18)	2595 (10)	1719 (17)	73 (17)	36 (6)	62 (14)	5 (9)	0 (15)	6 (8)
O(1)	−67 (8)	23 (5)	2757 (8)	31 (7)	23 (3)	33 (7)	1 (4)	6 (6)	−5 (4)
O(2)	−288 (9)	−385 (5)	491 (8)	31 (7)	23 (3)	39 (7)	7 (4)	−9 (7)	−5 (4)
O(3)	965 (9)	−1028 (5)	−138 (9)	40 (8)	24 (3)	54 (8)	−1 (4)	1 (8)	−12 (4)
O(4)	2584 (10)	−45 (7)	−481 (10)	50 (9)	36 (4)	60 (9)	−7 (5)	8 (8)	−6 (5)
O(5)	1631 (10)	−1643 (6)	2063 (10)	67 (10)	20 (3)	60 (8)	5 (5)	12 (8)	2 (4)
O(6)	160 (9)	995 (5)	3408 (8)	56 (9)	19 (3)	35 (7)	3 (4)	0 (7)	1 (4)
O(7)	−248 (10)	−415 (5)	4823 (9)	57 (9)	22 (3)	43 (8)	2 (5)	2 (8)	−1 (4)
O(8)	−1052 (11)	571 (6)	6194 (10)	64 (10)	32 (4)	47 (8)	1 (5)	8 (9)	−8 (5)
O(9)	381 (10)	1585 (5)	6073 (9)	54 (8)	23 (3)	33 (7)	2 (5)	−1 (7)	−3 (4)
O(10)	1310 (12)	2045 (7)	3059 (12)	67 (11)	30 (4)	94 (12)	6 (6)	15 (10)	7 (6)
O(11)	1491 (15)	−2111 (8)	3597 (14)	121 (14)	36 (5)	92 (13)	5 (8)	−2 (13)	7 (7)
O(12)	−1790 (18)	−703 (10)	4876 (19)	141 (20)	53 (7)	159 (22)	−4 (10)	3 (19)	30 (11)
O(13)	−24 (20)	271 (11)	7549 (17)	162 (18)	66 (7)	104 (15)	19 (11)	−12 (15)	14 (9)
O(14)	−1019 (14)	2064 (9)	6502 (15)	92 (14)	49 (6)	132 (16)	12 (8)	5 (14)	−35 (8)
O(15)	869 (15)	3010 (8)	2746 (15)	136 (16)	36 (5)	129 (16)	14 (8)	20 (15)	11 (8)

Table 2. *Observed and calculated structure factors*

H K L |F(OBS)| |F(CAL)|

[Dense multi-column table of observed and calculated structure factors; the individual numeric values are not legibly resolvable from the image.]

Table 2 (*cont.*)

10	2	5	12.89	12.69
11	2	5	18.25	18.03
0	3	5	93.30	106.55
1	3	5	56.71	61.08
2	3	5	12.00	10.27
3	3	5	23.69	20.45
4	3	5	58.92	61.31
5	3	5	36.59	37.16
6	3	5	46.60	46.84
7	3	5	25.63	21.71
8	3	5	18.19	17.89
9	3	5	14.20	12.41
11	3	5	17.14	13.68
0	4	5	74.43	76.43
1	4	5	41.72	45.00
2	4	5	94.30	99.50
3	4	5	30.27	28.67
4	4	5	62.48	61.37
5	4	5	37.48	33.73
6	4	5	54.93	57.97
7	4	5	22.91	23.49
8	4	5	19.80	20.95
9	4	5	17.56	15.21
10	4	5	14.05	13.69
0	5	5	23.27	17.00
1	5	5	36.95	36.74
2	5	5	37.84	33.81
3	5	5	45.71	39.50
4	5	5	49.22	46.39
5	5	5	22.17	19.50
6	5	5	29.30	23.92
7	5	5	40.94	42.38
8	5	5	20.49	21.06
9	5	5	31.14	31.54
10	5	5	20.65	17.32
11	5	5	9.38	6.53
0	6	5	13.16	15.08
1	6	5	60.33	63.64
2	6	5	43.77	45.80
3	6	5	25.53	22.88
4	6	5	47.91	45.25
5	6	5	37.37	35.81
6	6	5	22.96	24.11
7	6	5	11.27	8.95
8	6	5	31.82	35.64
9	6	5	37.01	46.29
10	6	5	16.98	15.57
0	7	5	29.14	26.06
1	7	5	40.62	43.92
2	7	5	60.80	59.05
3	7	5	58.55	60.22
4	7	5	50.01	46.66
5	7	5	15.31	14.20
6	7	5	9.85	10.74
7	7	5	16.30	14.64
9	7	5	23.43	24.96
10	7	5	18.71	15.33
11	7	5	10.85	18.14
0	8	5	35.17	27.85
1	8	5	9.70	4.80
2	8	5	72.07	75.00
3	8	5	22.54	15.63
4	8	5	27.05	22.37
5	8	5	17.04	17.31
6	8	5	33.44	32.06
7	8	5	23.69	22.90
8	8	5	10.17	11.18
9	8	5	11.85	10.18
10	8	5	9.38	12.44
0	9	5	64.21	64.78
1	9	5	24.43	21.70
2	9	5	26.00	25.20
3	9	5	42.77	41.79
4	9	5	26.66	25.84
5	9	5	40.20	41.53
7	9	5	18.56	19.12
8	9	5	15.57	13.39
9	9	5	18.56	20.10
0	10	5	30.77	29.34
1	10	5	57.92	58.98
2	10	5	14.57	14.65
3	10	5	27.47	27.20
4	10	5	13.63	12.67
5	10	5	36.06	40.20
6	10	5	16.83	18.28
7	10	5	7.18	11.78
8	10	5	20.44	20.05
10	10	5	13.26	13.40
0	11	5	22.91	22.75
1	11	5	21.33	20.57
2	11	5	23.22	23.47
3	11	5	31.87	26.23
4	11	5	34.07	37.75
5	11	5	14.41	17.37
6	11	5	21.23	17.42
7	11	5	22.07	23.36
8	11	5	10.69	13.67
9	11	5	17.14	16.83
10	11	5	13.21	12.84
0	12	5	17.72	16.26
1	12	5	29.41	28.71
2	12	5	22.96	23.89
3	12	5	14.26	12.55
4	12	5	23.59	22.13
5	12	5	28.57	28.03
6	12	5	17.82	17.55
7	12	5	10.59	9.32
10	12	5	13.05	13.80
0	13	5	18.50	18.67
1	13	5	26.58	23.05
2	13	5	24.32	20.21
3	13	5	31.08	33.27
4	13	5	5.14	8.42
5	13	5	20.49	20.93
6	13	5	11.79	16.25
7	13	5	12.00	14.40
8	13	5	14.36	13.13
0	14	5	10.43	8.03
1	14	5	25.32	25.46
2	14	5	21.39	19.33
3	14	5	22.70	19.74
4	14	5	10.33	10.57
5	14	5	10.54	8.79
6	14	5	20.08	23.10
0	15	5	27.73	28.82
1	15	5	14.83	14.37
2	15	5	14.20	10.41
4	15	5	10.59	12.86
5	15	5	12.00	14.13
6	15	5	17.98	19.45
7	15	5	15.36	20.06
8	15	5	14.15	19.29
0	16	5	31.92	34.35
1	16	5	6.55	5.52
2	16	5	26.99	26.97
3	16	5	5.14	3.54
5	16	5	17.14	18.28
1	17	5	18.77	18.32
2	17	5	15.36	15.43
3	17	5	26.78	26.72
4	17	5	15.99	17.96
5	17	5	14.36	15.86
6	17	5	10.75	13.60
0	18	5	19.24	19.33
1	18	5	19.29	16.96
2	18	5	19.29	10.13
3	18	5	13.08	14.56
4	18	5	14.00	17.78
5	18	5	10.69	14.34
0	19	5	9.96	9.70
1	19	5	9.75	10.66
2	19	5	9.28	12.30
4	19	5	19.55	22.07
1	20	5	13.52	4.29
2	20	5	22.17	18.39
4	20	5	11.79	10.20
0	22	5	14.36	5.84
1	22	5	8.70	10.51
2	22	5	12.84	10.55
0	0	6	59.75	62.59
1	0	6	10.38	6.99
2	0	6	29.35	25.37
4	0	6	94.72	95.83
5	0	6	12.84	10.50
6	0	6	19.76	15.11
7	0	6	32.66	31.21
8	0	6	23.53	25.51
9	0	6	14.10	14.62
10	0	6	27.57	24.01
0	1	6	39.42	41.29
1	1	6	74.64	74.53
2	1	6	40.57	39.72
3	1	6	41.62	46.26
4	1	6	43.98	42.45
5	1	6	39.36	34.21
6	1	6	30.82	25.90
7	1	6	27.78	27.58
8	1	6	24.79	24.72
0	2	6	17.40	16.45
1	2	6	31.61	27.06
2	2	6	26.89	25.19
3	2	6	55.93	48.75
4	2	6	30.72	31.44
5	2	6	15.46	8.74
6	2	6	17.19	13.31
7	2	6	48.22	50.61
8	2	6	33.97	33.20
0	3	6	13.08	15.33
1	3	6	21.91	24.19
2	3	6	78.89	83.65
3	3	6	40.94	28.12
4	3	6	38.26	36.66
5	3	6	51.73	53.27
7	3	6	29.67	29.85
8	3	6	33.34	31.10
9	3	6	18.40	18.91
0	4	6	74.90	85.62
1	4	6	39.31	39.21
2	4	6	51.53	44.02
3	4	6	60.38	56.66
4	4	6	30.14	28.56
5	4	6	16.25	16.55
6	4	6	33.97	33.15
7	4	6	15.52	13.51
8	4	6	35.49	36.68
9	4	6	10.56	13.70
10	4	6	10.48	12.19
0	5	6	21.54	19.09
1	5	6	29.88	31.92
2	5	6	15.20	11.48
3	5	6	23.64	21.91
4	5	6	62.22	65.48
5	5	6	23.33	20.72
6	5	6	42.82	41.37
8	5	6	18.61	15.11
9	5	6	10.72	19.30
0	6	6	39.94	39.47
1	6	6	63.58	61.42
2	6	6	45.44	41.29
3	6	6	18.97	17.02
4	6	6	25.05	21.51
5	6	6	38.05	34.15
6	6	6	16.77	18.62
7	6	6	21.49	26.55
8	6	6	15.10	18.13
10	6	6	17.24	12.50
0	7	6	9.17	1.04
1	7	6	25.32	24.74
2	7	6	44.87	44.58
4	7	6	42.40	38.22
5	7	6	28.15	23.98
7	7	6	13.47	7.28
8	7	6	23.90	24.41
0	8	6	28.36	31.65
1	8	6	52.36	54.16
2	8	6	26.05	18.36
3	8	6	22.22	22.06
4	8	6	30.14	34.49
5	8	6	35.07	32.96
7	8	6	31.82	32.48
8	8	6	15.57	15.93
0	9	6	38.53	37.50
1	9	6	36.80	35.95
2	9	6	25.47	22.89
3	9	6	27.78	27.68
4	9	6	4.93	6.16
5	9	6	29.88	30.65
6	9	6	17.35	19.74
7	9	6	20.70	17.30
8	9	6	24.56	27.23
0	10	6	39.52	35.58
1	10	6	42.40	41.32
2	10	6	13.73	12.92
3	10	6	51.05	53.31
4	10	6	20.49	22.33
5	10	6	38.16	42.13
6	10	6	25.26	25.96
7	10	6	26.89	29.57
8	10	6	20.02	14.38
1	11	6	10.41	14.44
2	11	6	35.33	34.35
3	11	6	13.16	9.01
4	11	6	20.49	22.11
5	11	6	23.09	25.14
6	11	6	29.56	31.22
7	11	6	23.90	23.78
8	11	6	18.29	21.34
0	12	6	42.56	46.16
1	12	6	35.43	35.08
2	12	6	13.16	10.40
3	12	6	16.83	15.62
4	12	6	21.96	20.05
5	12	6	15.25	15.43
6	12	6	24.43	27.20
8	12	6	29.30	33.50
1	13	6	28.72	28.26
2	13	6	23.74	23.00
3	13	6	22.49	18.36
4	13	6	27.73	31.96
5	13	6	19.60	19.76
0	14	6	24.58	22.57
1	14	6	33.34	32.98
2	14	6	15.99	14.04
3	14	6	16.25	16.95
0	15	6	3.46	0.49
1	15	6	7.55	7.83
2	15	6	24.16	24.53
3	15	6	20.02	19.72
0	16	6	17.04	16.24
1	16	6	12.84	12.62
2	16	6	14.20	12.32
3	16	6	5.24	7.67
4	16	6	16.88	13.62
1	17	6	24.69	24.59
3	17	6	18.29	18.31
3	18	6	12.21	11.54
4	18	6	13.47	9.22
0	19	6	13.89	12.66
2	19	6	18.19	15.82
3	19	6	9.02	6.44
5	19	6	15.15	6.53
2	20	6	12.84	11.35
3	20	6	15.62	14.65
4	20	6	18.19	17.82
1	21	6	13.11	11.91
3	21	6	11.58	11.93
4	21	6	8.75	8.96
1	22	6	7.39	9.29
1	0	7	15.46	13.78
2	0	7	85.44	96.30
3	0	7	30.61	33.32
4	0	7	6.76	1.58
5	0	7	26.05	23.42
6	0	7	35.12	34.73
7	0	7	15.78	15.20
8	0	7	32.66	37.37
9	0	7	12.63	8.53
11	0	7	16.51	11.26
0	1	7	58.02	64.23
1	1	7	27.31	20.70
2	1	7	36.74	32.29
3	1	7	52.63	46.38
4	1	7	40.88	39.40
5	1	7	44.13	41.85
6	1	7	18.92	19.34
7	1	7	14.99	11.57
9	1	7	13.89	16.59
10	1	7	14.26	18.26
11	1	7	13.05	14.76
0	2	7	10.17	11.87
1	2	7	54.62	50.92
2	2	7	14.47	16.75
3	2	7	28.04	22.29
4	2	7	26.31	26.07
5	2	7	48.28	45.85
7	2	7	17.45	13.14
8	2	7	17.93	13.95
0	3	7	29.82	31.51
1	3	7	17.04	13.30
2	3	7	17.30	13.63
3	3	7	18.19	13.74
4	3	7	46.05	35.90
5	3	7	18.14	18.29
6	3	7	31.14	30.65
7	3	7	20.34	19.41
8	3	7	26.63	25.62
9	3	7	16.14	14.90
10	3	7	23.38	25.50
0	4	7	15.89	20.03
1	4	7	45.76	41.76
2	4	7	58.39	54.61
3	4	7	25.84	23.60
4	4	7	13.05	10.07
5	4	7	25.95	23.00
6	4	7	22.96	21.18
7	4	7	14.57	12.41
11	4	7	15.36	12.58
0	5	7	37.37	37.01
1	5	7	29.77	32.15
2	5	7	48.54	50.05
3	5	7	41.41	43.57
4	5	7	37.74	38.98
5	5	7	33.86	33.10
6	5	7	28.57	26.45
7	5	7	19.66	19.14
8	5	7	15.07	15.65
0	6	7	13.15	13.69
1	6	7	42.77	42.14
2	6	7	49.64	45.23
3	6	7	27.68	25.79
4	6	7	26.31	30.24
6	6	7	15.88	17.64
7	6	7	33.39	34.21
9	6	7	21.70	24.52
10	6	7	15.46	13.84
11	6	7	6.12	12.08
0	7	7	30.66	29.53
1	7	7	45.18	40.52
2	7	7	34.44	36.15
4	7	7	20.18	16.75
5	7	7	14.52	15.11
6	7	7	19.97	18.93
7	7	7	18.67	16.67
9	7	7	13.05	12.30
1	8	7	16.46	13.17
2	8	7	24.69	22.41
3	8	7	19.81	20.31
4	8	7	15.67	14.66
5	8	7	20.08	25.18
6	8	7	19.81	21.58
7	8	7	37.69	36.96
8	8	7	15.20	18.40
9	8	7	23.38	21.48
11	8	7	11.22	9.31
0	9	7	29.14	29.98
1	9	7	35.89	34.69
2	9	7	25.58	25.22
3	9	7	41.25	43.62
4	9	7	13.31	12.12
5	9	7	13.73	13.20
6	9	7	24.32	23.36
7	9	7	9.80	11.75
0	10	7	4.19	2.30
1	10	7	14.32	36.52
2	10	7	17.04	16.40
3	10	7	29.77	31.42
4	10	7	27.41	24.41
5	10	7	30.62	31.42
6	10	7	22.28	23.27
7	10	7	26.94	25.51
8	10	7	16.51	15.62
0	11	7	8.33	12.18
2	11	7	10.54	13.62
3	11	7	21.96	19.52
4	11	7	35.28	38.14
5	11	7	26.47	26.65
6	11	7	19.71	23.16
7	11	7	15.36	15.46
1	12	7	14.20	13.78
2	12	7	42.35	44.75
3	12	7	17.30	15.42
4	12	7	13.20	14.17
5	12	7	13.89	14.52
6	12	7	11.53	11.72
0	13	7	17.93	16.63
1	13	7	13.00	8.35
2	13	7	27.73	32.20
3	13	7	37.11	37.72
4	13	7	13.63	15.63
5	13	7	26.42	31.85
9	13	7	13.68	17.68
0	14	7	24.32	27.87
1	14	7	25.00	24.80
2	14	7	30.62	30.26
3	14	7	32.60	36.45
4	14	7	13.73	12.22
5	14	7	24.06	19.58
0	15	7	24.95	22.55
1	15	7	18.14	18.21
2	15	7	16.41	14.69
3	15	7	6.54	11.64
4	15	7	13.79	15.40
5	15	7	18.50	18.68
7	15	7	15.13	15.62
1	16	7	20.18	21.13
2	16	7	26.05	25.32
3	16	7	11.32	19.11
5	16	7	13.00	19.02
7	16	7	13.63	15.16
1	17	7	25.42	25.59
3	17	7	8.12	9.37
4	17	7	10.01	7.49
5	17	7	12.74	14.17
6	17	7	14.73	14.63
7	17	7	11.95	15.37
0	18	7	15.36	16.52
3	18	7	14.73	13.51
6	18	7	9.23	3.53
2	19	7	11.99	13.88
3	19	7	9.79	11.62
4	20	7	10.38	11.10
1	21	7	9.82	11.60
1	22	7	6.81	11.64
3	22	7	7.76	10.09
0	0	8	81.09	90.10
1	0	8	25.74	25.83
2	0	8	15.46	13.17
3	0	8	3.51	3.56
4	0	8	42.67	49.30
7	0	8	21.18	20.46
8	0	8	10.96	9.52
9	0	8	27.47	29.02
10	0	8	21.28	22.68
11	0	8	11.32	12.72
0	1	8	31.50	33.97
1	1	8	14.10	14.98
2	1	8	23.95	26.17
3	1	8	18.97	16.37
4	1	8	16.67	16.69
5	1	8	24.53	18.05
7	1	8	14.62	10.30
8	1	8	16.30	20.53
10	1	8	15.52	14.64
11	1	8	13.42	14.95
0	2	8	2.25	2.77
1	2	8	26.99	28.90
2	2	8	20.91	22.18
3	2	8	20.29	21.33
4	2	8	12.48	17.37
5	2	8	9.64	9.61
7	2	8	18.61	21.26
8	2	8	16.35	17.38
9	2	8	12.53	14.12
10	2	8	25.84	30.98
0	3	8	10.59	4.10
1	3	8	45.97	54.48
2	3	8	31.40	30.58
3	3	8	22.17	19.65
4	3	8	24.22	22.88
6	3	8	24.32	20.04
8	3	8	15.67	12.16
9	3	8	12.58	13.39
11	3	8	13.31	12.38
0	4	8	40.36	43.48
1	4	8	10.83	19.25
2	4	8	12.79	11.55
3	4	8	24.65	22.12
4	4	8	27.99	29.71
5	4	8	17.67	10.25
6	4	8	10.90	8.78
0	5	8	27.26	26.52
7	4	8	13.64	11.06
8	4	8	13.21	18.36
1	5	8	21.00	23.12
2	5	8	32.76	36.64
3	5	8	13.73	12.19
4	5	8	25.37	23.27
5	5	8	28.99	29.69
6	5	8	23.81	23.00
7	5	8	21.02	21.96
10	5	8	12.59	14.35
11	5	8	14.05	15.99
0	6	8	32.29	29.63
1	6	8	12.00	14.10
2	6	8	16.67	15.73
3	6	8	47.91	47.54
4	6	8	35.80	33.36
5	6	8	18.97	12.60
6	6	8	27.10	22.13
7	6	8	29.77	32.73
8	6	8	15.17	9.86
1	7	8	16.25	15.22
2	7	8	25.79	26.58
3	7	8	24.06	24.74
4	7	8	32.39	37.16
5	7	8	26.21	26.60
6	7	8	13.42	16.23
7	7	8	21.65	26.78
0	8	8	36.22	33.36
1	8	8	35.22	37.41
2	8	8	17.72	18.71
3	8	8	11.64	8.16
4	8	8	21.91	23.32
5	8	8	16.09	17.23
6	8	8	26.63	29.29
7	8	8	21.96	21.70
8	8	8	16.30	19.69
1	9	8	39.26	35.69
2	9	8	22.75	19.79
3	9	8	16.33	16.44
4	9	8	21.02	22.91
5	9	8	31.34	34.63
6	9	8	28.04	32.33
1	10	8	22.22	21.18
2	10	8	16.19	17.33
3	10	8	17.24	15.61
4	10	8	22.12	19.15
5	10	8	12.00	11.70
7	10	8	16.25	21.69
0	11	8	30.66	32.6[illegible]
1	11	8	12.06	12.79
3	11	8	18.51	21.37
4	11	8	12.48	11.74
5	11	8	21.28	21.41
7	11	8	11.53	10.67
0	12	8	46.91	48.75
2	12	8	17.19	14.62
3	12	8	12.58	10.58
4	12	8	6.92	10.73
5	12	8	15.31	13.22
0	13	8	10.38	12.45
1	13	8	35.28	36.77
3	13	8	30.56	27.65
5	13	8	17.87	15.03
0	14	8	17.06	21.10
1	14	8	14.99	14.63
2	14	8	9.17	7.14
3	14	8	23.50	23.37
4	14	8	13.63	11.71
5	14	8	15.52	17.00
6	14	8	12.58	12.68
0	15	8	36.85	40.13
1	15	8	10.75	6.43
2	15	8	24.95	25.37
3	15	8	15.25	14.95
4	15	8	17.24	18.32
5	15	8	16.98	19.78
6	15	8	14.26	18.70
1	16	8	11.53	11.27
2	16	8	12.53	10.90
3	16	8	14.62	12.77
4	16	8	13.84	14.03
2	17	8	15.78	13.57
4	17	8	13.68	13.73
5	17	8	9.75	12.15
6	17	8	10.54	11.95
0	18	8	12.63	13.53
1	18	8	9.23	10.65
3	18	8	14.89	17.56
1	19	8	12.42	13.00
4	0	8	7.18	5.98
1	0	9	26.66	30.28
2	0	9	49.06	46.94
4	0	9	14.15	13.30
0	1	9	23.38	18.93
1	1	9	14.73	13.58
2	1	9	18.77	17.28
3	1	9	36.53	40.62
4	1	9	13.52	14.24
0	2	9	42.04	44.[illegible]
1	2	9	25.05	24.15
2	2	9	27.85	30.17
4	2	9	11.06	21.26
0	3	9	53.36	57.03
1	3	9	15.22	15.76
2	3	9	19.41	14.37
4	3	9	16.67	13.14
0	4	9	14.78	15.63
1	4	9	22.38	20.12
2	4	9	31.71	31.78
3	4	9	15.11	18.19
4	4	9	11.48	8.81
0	5	9	18.50	14.73
1	5	9	30.45	28.68
2	5	9	37.74	36.44
3	5	9	25.68	23.49
4	5	9	32.18	33.26
0	6	9	16.29	16.95
1	6	9	21.02	23.13
2	6	9	16.93	11.70
4	6	9	16.58	18.05
2	7	9	14.89	10.99
3	7	9	45.08	49.65
4	7	9	27.57	33.03
0	8	9	16.14	13.78
1	8	9	19.67	21.62
2	8	9	41.67	40.63
3	8	9	16.46	12.40
4	8	9	23.90	27.92
1	9	9	33.81	33.95
2	9	9	19.03	19.55
3	9	9	19.03	15.50
4	9	9	33.18	34.61
0	10	9	48.28	51.22
1	10	9	35.80	42.26
2	10	9	13.58	7.64
4	10	9	12.95	10.49
0	11	9	31.24	31.91
1	11	9	25.69	28.40
2	11	9	17.93	15.72
3	11	9	16.88	15.31
4	11	9	14.52	10.17
2	12	9	26.90	24.62
3	12	9	14.78	6.95
4	12	9	17.77	16.67
1	13	9	27.10	26.15
3	13	9	16.14	14.33
4	13	9	11.16	11.32
0	14	9	19.92	21.62
1	14	9	19.55	15.31
2	14	9	20.55	22.12
3	14	9	20.35	27.83
0	15	9	8.81	9.32
2	15	9	15.99	12.39
3	16	9	10.75	8.66
2	17	9	11.58	5.04
3	17	9	11.11	12.31
4	17	9	13.94	12.30
0	18	9	12.48	[illegible]
1	18	9	14.94	[illegible]
2	18	9	12.68	11.36
2	19	9	11.90	8.76
1	20	9	17.48	3.50
2	20	9	14.94	13.59
0	0	10	32.92	37.77
1	0	10	16.35	17.64
2	0	10	15.78	15.62
3	0	10	33.65	35.38
4	0	10	46.28	44.81
0	1	10	26.10	30.72
1	1	10	16.35	15.31
2	1	10	33.49	31.51
3	1	10	30.09	27.96
4	1	10	12.74	9.39
1	2	10	14.62	17.20
2	2	10	14.99	11.68
3	2	10	31.82	30.18
4	2	10	31.55	33.46
1	3	10	30.56	30.83
2	3	10	33.34	36.52
3	3	10	24.58	23.95
4	3	10	29.67	32.48
0	4	10	43.87	50.55
1	4	10	12.06	11.21
2	4	10	17.19	16.08
3	4	10	19.97	17.78
4	4	10	12.00	11.46
2	5	10	32.92	33.54
3	5	10	25.68	20.24
4	5	10	29.20	35.72
0	6	10	19.18	13.18
1	6	10	22.85	20.72
2	6	10	24.01	20.85
3	6	10	16.72	13.20
4	6	10	26.08	23.69
0	7	10	19.34	13.51
1	7	10	30.14	24.13
3	7	10	34.66	35.81
4	7	10	15.84	16.87
0	8	10	30.61	31.05
1	8	10	9.80	8.52
2	8	10	17.93	16.42
3	8	10	15.52	18.67
0	9	10	28.72	34.66
1	9	10	14.57	6.98
3	9	10	27.31	25.93
4	9	10	12.16	14.54
1	10	10	19.18	18.94
2	10	10	17.98	11.35
3	10	10	31.71	30.25
4	10	10	12.11	13.72
0	11	10	19.55	18.35
1	11	10	13.89	15.52
2	11	10	21.96	31.92
3	11	10	12.32	11.05
4	11	10	16.35	15.57
0	12	10	14.12	14.05
1	12	10	13.10	7.76
2	12	10	16.98	15.29
3	12	10	11.27	12.30
4	12	10	17.87	15.86
0	13	10	13.16	13.82
1	13	10	19.24	20.48
2	13	10	12.37	10.39
3	13	10	20.06	11.28
4	13	10	12.37	10.87
1	14	10	15.20	14.03
2	14	10	13.94	12.85
3	14	10	9.85	11.78
4	14	10	12.02	11.41
1	15	10	10.80	7.56
3	15	10	14.19	13.13
4	15	10	10.01	11.56
0	16	10	14.99	14.03
2	16	10	14.47	13.68
1	17	10	11.74	8.48
2	17	10	11.48	7.91
0	18	10	7.97	3.98
1	18	10	10.96	12.29
3	18	10	11.74	9.30
3	19	10	9.64	2.17
1	0	11	28.36	29.11
2	0	11	31.45	33.27
1	1	11	32.76	38.08
4	1	11	22.54	23.25
0	2	11	14.15	15.59
3	2	11	14.05	12.01
0	3	11	4[illegible].26	42.18
1	3	11	27.78	18.98
2	3	11	24.32	22.38
3	3	11	30.35	31.10
1	4	11	46.49	49.10
2	4	11	20.08	18.34
3	4	11	17.51	12.26
0	5	11	33.28	30.14
1	5	11	13.21	13.76
2	5	11	44.97	45.[illegible]
3	5	11	27.31	26.13
4	5	11	16.56	19.20
[illegible]	6	11	[illegible]	25.8[illegible]
1	6	11	33.23	30.35
2	6	11	14.68	12.57
3	6	11	26.05	25.14
0	7	11	16.77	14.79
1	7	11	25.26	22.49
2	7	11	22.59	21.69
4	7	11	18.77	19.76
0	8	11	23.27	21.26
1	8	11	24.01	24.51
2	8	11	21.28	24.35
0	9	11	31.19	31.07
1	9	11	25.79	22.91
2	9	11	19.87	20.52
3	9	11	11.27	10.29
4	9	11	11.79	5.39
1	10	11	12.95	11.00
2	10	11	17.56	16.91
2	11	11	14.10	6.07
3	11	11	14.78	16.12
1	12	11	11.01	8.88
2	12	11	15.41	14.65
3	12	11	13.05	13.86
2	13	11	14.99	11.43
3	13	11	17.87	17.94
1	14	11	12.37	8.78
3	14	11	11.43	7.38
1	15	11	16.54	11.16
1	17	11	9.23	11.43
1	18	11	7.23	10.78
3	18	11	8.33	9.79
0	0	12	12.03	13.51
1	0	12	12.37	4.14
2	0	12	18.01	16.12
3	0	12	11.32	9.49
4	0	12	13.52	14.24
1	1	12	13.64	13.37
2	1	12	18.56	16.47
3	1	12	31.34	32.85
4	1	12	18.03	18.81
0	2	12	14.83	13.17
1	2	12	12.37	12.92
2	2	12	12.63	8.46
4	2	12	14.20	17.22
0	3	12	14.78	12.00
1	3	12	22.28	20.20
2	3	12	16.25	14.82
3	3	12	18.40	15.56
0	4	12	32.39	29.43
1	4	12	21.75	23.60
3	4	12	15.88	12.20
0	5	12	29.04	26.49
1	5	12	19.87	19.87
0	6	12	21.54	24.31
1	6	12	17.24	17.19
3	6	12	16.93	18.00
0	7	12	20.91	22.24
2	7	12	17.35	17.27
4	7	12	14.31	15.17
0	8	12	22.80	21.80
2	8	12	16.35	13.52
3	8	12	11.64	9.65
4	8	12	14.10	12.08
1	9	12	13.10	12.86
2	9	12	19.39	19.90
4	9	12	16.62	20.14
1	10	12	16.72	16.18
2	10	12	18.97	13.66
1	11	12	14.78	12.06
2	11	12	13.05	7.87
3	11	12	19.55	19.22
1	12	12	12.06	11.64
0	13	12	17.51	23.03
1	13	12	9.64	11.54
1	14	12	9.12	7.73
3	14	12	9.33	8.49
1	0	13	16.67	18.90
2	0	13	12.95	10.32
0	1	13	18.56	21.88
2	1	13	14.62	15.96
3	1	13	13.05	10.95
0	2	13	9.49	9.97
1	2	13	13.16	8.77
1	3	13	13.73	14.84
3	3	13	12.16	7.38
1	4	13	14.20	13.14
2	4	13	14.41	12.69
3	4	13	19.08	20.56
4	4	13	7.13	12.18
2	5	13	17.09	11.05
3	5	13	14.00	9.55
4	5	13	10.69	11.33
1	6	13	15.52	12.45
3	6	13	8.28	6.22
4	6	13	9.75	11.74
0	7	13	10.64	12.61
1	7	13	10.38	8.74
2	7	13	15.20	13.82
4	7	13	11.69	15.46
1	8	13	10.85	11.42
4	8	13	14.68	14.77
0	9	13	12.68	15.73
1	9	13	9.17	8.16
3	9	13	11.53	11.48
0	10	13	13.84	15.90
1	10	13	12.48	16.76
3	10	13	11.11	11.34
1	11	13	10.96	10.06
0	12	13	8.23	10.06
2	12	13	10.75	8.42
3	13	13	8.12	7.77
1	14	13	7.97	6.37
3	15	13	6.76	8.70
0	0	14	9.38	7.05
4	0	14	11.58	11.38
0	1	14	14.31	14.32
2	1	14	11.53	7.29
0	2	14	8.49	11.49
2	2	14	14.30	9.31
3	2	14	10.17	8.69
2	3	14	14.83	15.81
3	3	14	10.01	10.00
1	4	14	10.90	12.08
3	4	14	7.44	5.10
0	5	14	12.16	14.27
3	5	14	8.18	5.74
3	6	14	7.97	3.62
1	7	14	13.16	18.40
3	7	14	9.12	4.66
4	7	14	9.17	9.80
1	8	14	7.34	8.54
2	8	14	16.09	6.55
3	8	14	13.26	15.49
3	9	14	9.96	10.52
4	9	14	9.75	10.78
1	10	14	13.26	17.75
3	10	14	8.39	12.65
1	11	14	8.75	9.17
3	11	14	7.71	10.30
0	12	14	8.18	9.61
1	0	15	6.92	6.93
2	0	15	11.27	12.60
1	1	15	11.11	11.47
2	1	15	10.69	5.90
1	2	15	11.65	6.39
2	4	15	6.61	7.30
1	5	15	7.02	0.99
2	5	15	8.70	9.95
1	6	15	7.29	3.11
1	7	15	9.43	10.07
1	10	15	5.61	6.87

Successive calculations of Fourier and difference Fourier syntheses starting with these refined parameters enabled us to locate all the forty-nine atoms belonging to the molecule. Oxygen atoms were identified on the electron density map with the help of chemical and structural considerations. The R value at this stage was 0·18. Further refinement was carried out by the block-matrix least-squares method. Ten cycles of calculation, the last two of which included the anisotropic thermal parameters for all the forty nine atoms, reduced the R value to 0·11 for 1844 reflexions. The weighting functions used for this calculations were:

$$\sqrt{w}=21/F_o, \quad \text{when } 21 < F_o,$$
$$\sqrt{w}=1\cdot0, \quad \text{when } 3 < F_o \le 21,$$
$$\sqrt{w}=0, \quad \text{when } F_o \le 3.$$

The final atomic parameters and their standard deviations are given in Table 1. The observed and calculated structure factors are listed in Table 2. A final three-dimensional Fourier synthesis was then calculated; a composite projection of the electron density map is shown in Fig. 2(a). Fig. 2(b) shows the conformation and thermal vibrations of the molecule drawn by the plotter program ORTEP (Johnson, 1965). The ellipsoids cover a 50% probability area of finding the centre of the atom in it.

Absolute configuration

The absolute configuration of the structure was determined by the anomalous dispersion method. Dispersion corrections for the bromine scattering factor for Cu $K\alpha$ radiation of $\Delta f' = -0\cdot9$ and $\Delta f'' = 1\cdot5$ were used (Dauben & Templeton, 1955). The structure factors for the Friedel pairs of reflexions were calculated and compared with the observed values by assuming a
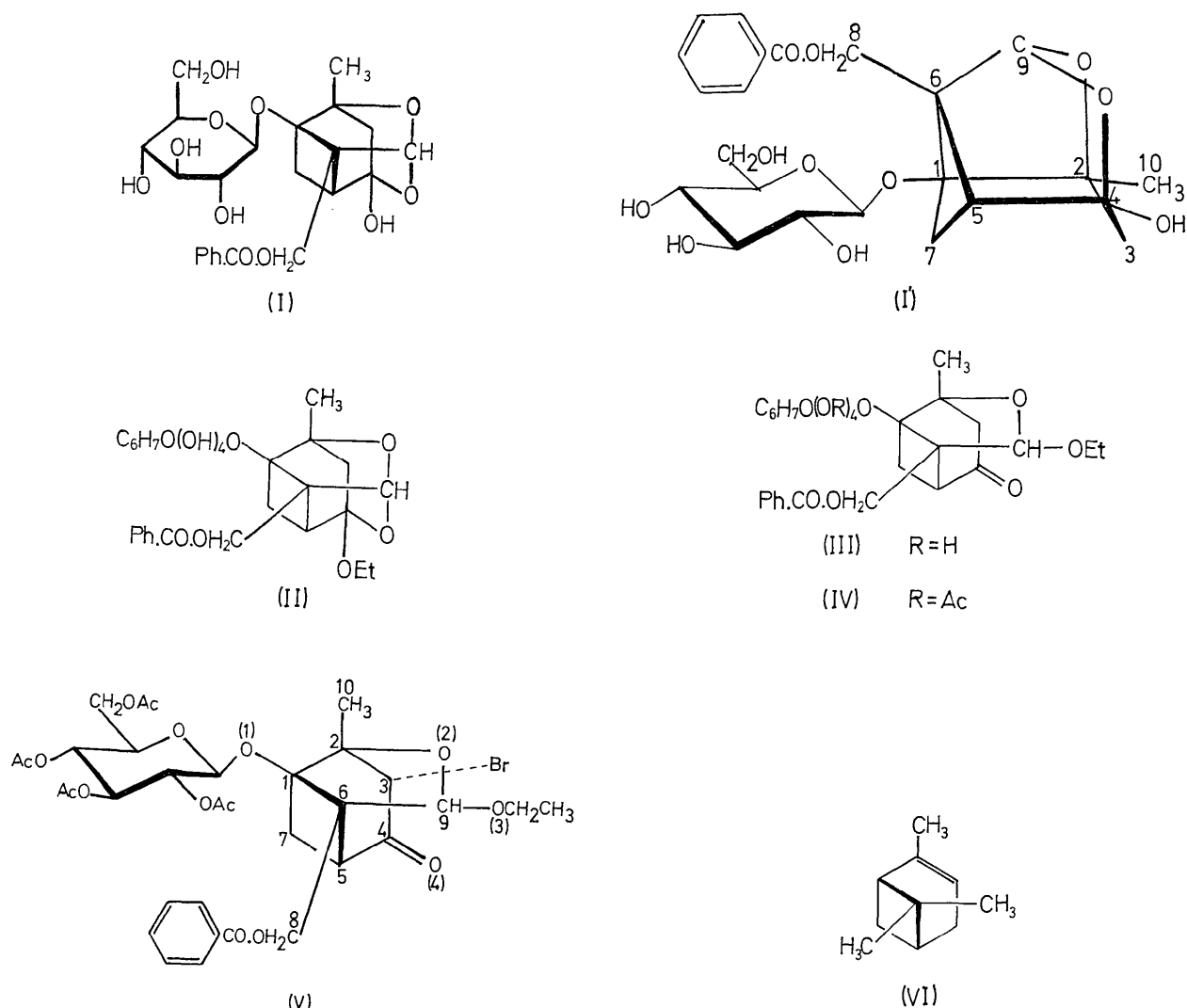

Fig. 1. Chemical formulae of (I) paeoniflorin, (I') paeoniflorin showing its stereo-structure, (II) ethanolysis product K_1, (III) ethanolysis product K_2, (IV) K_2-acetate, (V) brominated compound studied by X-ray diffraction, (VI) ($+$)-α-pinene.

right-handed set of axes. Fourteen pairs of hkl and $h\bar{k}l$ reflexions showed significant intensity differences in the lth layer Weissenberg photographs. The results are shown in Table 3. A comparison between observed and calculated intensities indicated that the assumed configuration was actually the antipode of the true structure. The absolute configuration of paeoniflorin itself is then established as Fig. 1(I') which corresponds to that of $(+)$-α-pinene (VI).

Table 3. *Comparison of the observed and calculated intensity ratios used to establish the absolute configuration*

hkl	$\dfrac{\|F_c\,(hkl)\|^2}{\|F_c\,(h\bar{k}l)\|^2}$	$\dfrac{I_o\,(hkl)}{I_o\,(h\bar{k}l)}$
111	1·231	<1
711	1·341	<1
811	0·506	>1
121	0·866	>1
631	1·133	<1
731	1·101	<1
831	0·812	>1
241	0·917	>1
441	0·604	>1
751	1·249	<1
181	1·137	<1
481	1·125	<1
2,12,1	0·911	>1
5,12,1	1·260	<1

This absolute configuration agrees with that obtained when the coordinate system was settled assuming that the glucosyl group of the compound would take the D configuration. This assumption is therefore fully confirmed by the present direct determination based on the anomalous dispersion method. All figures presented in this paper are drawn with the correct absolute configuration.

Discussion of the structure

The molecular structure of the bromo-derivative of paeoniflorin determined by the present analysis is shown in Fig. 1(V) and Fig. 2(b). The structure of paeoniflorin is therefore deduced as shown in Fig. 1(I'). As was proposed by chemical and spectroscopic studies, it is a glucoside of a pinane type monoterpene which possesses a novel cage-like structure composed of an acetal and a hemiketal group. The glucosyl moiety of paeoniflorin is linked to a tertiary OH of the aglycone through a β linkage.

Paeoniflorin, when treated with TsOH in ethanol solution, undergoes ethanolysis to yield product K_1 (II) and product K_2 (III). Bromination of product K_2-acetate (IV) with Br_2 occurred at the active methylene next to the ketone group. The bromine atom of V is found to be linked in the axial direc-
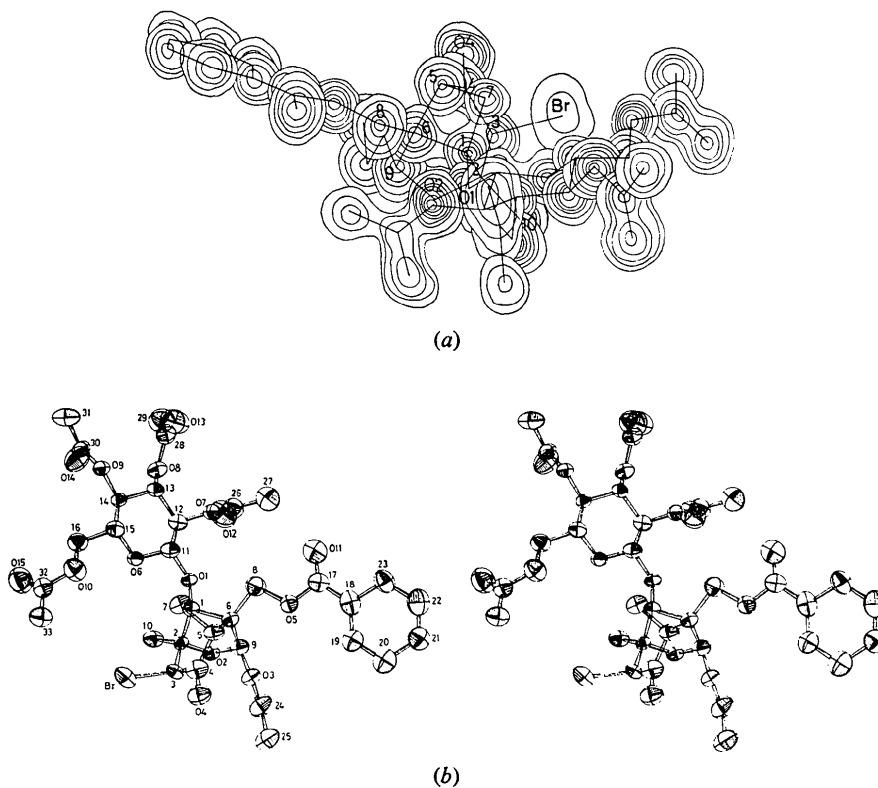

(a)

(b)

Fig. 2. (a) Composite projection of the electron density distribution along the c axis. Contours are drawn at 2,3,4... e.Å^{-3}, those for the bromine atom are at 10, 20 e.Å^{-3}. (b) Stereoscopic view of the molecular structure drawn by *ORTEP* showing absolute configuration, conformation and atomic thermal vibrations.

tion by the present X-ray analysis. This orientation of the bromine atom is in accordance with the discussion given by Corey & Sneen (1956) which stated that bromine substitution would occur *via* an enol intermediate in the axial direction nearly parallel to the carbonyl carbon *p*-orbital.

The present X-ray study also revealed, as was supposed from spectroscopic data, that the glucosyl linkage is β, that the glucosyl group takes a so-called *C*1 form, and that the acetyl groups of the glucosyl moiety all take *trans* conformation, as was observed in the derivative of loganin determined by X-ray methods (Lentz & Rossmann, 1969).

The bond lengths and angles of the molecule (V), calculated from the coordinates given in Table 1, are shown in Figs. 3 and 4 respectively. In Table 4 are listed the bond lengths arranged in groups of similar type. The mean bond lengths averaged over each type of bond are in agreement with the normally accepted values, although some of the bond lengths are longer. Thus the lengths of C(24)–C(25) and C(28)–C(29), and those of C(1)–C(6), C(1)–C(7), C(5)–C(6) and C(5)–C(7) are considerable. The first two bonds are situated at the terminal portion of the molecule and the errors in bond lengths seem to be appreciable owing to the large thermal vibrations, while the other four are involved in the four-membered ring and the longer bonds are the common feature of such a strongly strained system (Fukazawa, Itô & Iitaka, 1969). The distance between C(4) and C(9) is 2·90 Å and that between C(4) and O(3) is 2·56 Å. The latter two atoms seem to be located at positions little different from those they would occupy in the molecule of paeoniflorin.

Table 4. *Bond lengths arranged in groups of similar bonds*

E.s.d.'s are shown in parentheses.

C–Br		C=O	
C(3)–Br	1·95 (0·02) Å	C(4)=O(4)	1·23 (0·02) Å
C–O		C(17)=O(11)	1·20 (0·03)
C(1)—O(1) Å	1·46 (0·02)	C(26)=O(12)	1·21 (0·04)
C(2)—O(2)	1·45 (0·02)	C(28)=O(13)	1·14 (0·04)
C(8)—O(5)	1·48 (0·03)	C(30)=O(14)	1·20 (0·03)
C(9)—O(2)	1·40 (0·02)	C(32)=O(15)	1·23 (0·03)
C(9)—O(3)	1·41 (0·02)	average value 1·20 Å	
C(11)—O(1)	1·44 (0·02)		
C(11)—O(6)	1·40 (0·02)	**O–C(*sp²*) (O-acyl)**	
C(12)—O(7)	1·44 (0·02)	O(5)—C(17)	1·35 (0·02) Å
C(13)—O(8)	1·43 (0·02)	O(7)—C(26)	1·35 (0·03)
C(14)—O(9)	1·47 (0·02)	O(8)—C(28)	1·44 (0·03)
C(15)—O(6)	1·42 (0·02)	O(9)—C(30)	1·37 (0·02)
C(16)—O(10)	1·44 (0·03)	O(10)—C(32)	1·38 (0·03)
C(24)—O(3)	1·47 (0·03)	average value 1·38 Å	
average value 1·44 Å			

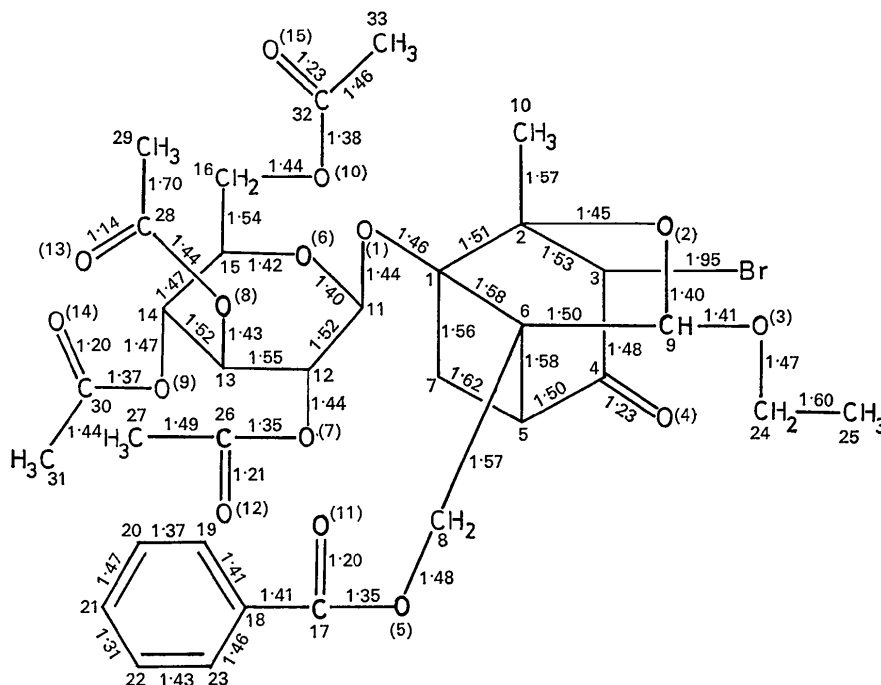| C(*sp³*)–C(*sp³*)		C(*sp²*)–C(*sp³*)	
C(1)—C(2)	1·52 (0·02) Å	C(3)—C(4)	1·48 (0·03) Å
C(1)—C(6)	1·58 (0·02)	C(4)—C(5)	1·50 (0·03)
C(1)—C(7)	1·56 (0·03)	C(17)—C(18)	1·41 (0·03)
C(2)—C(3)	1·53 (0·03)	C(26)—C(27)	1·49 (0·04)
C(2)—C(10)	1·57 (0·03)	C(28)—C(29)	1·70 (0·04)
C(5)—C(6)	1·58 (0·03)	C(30)—C(31)	1·44 (0·03)
C(5)—C(7)	1·62 (0·03)	C(32)—C(33)	1·46 (0·03)
C(6)—C(8)	1·57 (0·03)	average value [excluding	
C(6)—C(9)	1·50 (0·03)	C(28)–C(29)] 1·46 Å	
C(11)—C(12)	1·52 (0·03)		
C(12)—C(13)	1·55 (0·02)	**Aromatic C–C**	
C(13)—C(14)	1·52 (0·02)	C(18)—C(19)	1·41 (0·03) Å
C(14)—C(15)	1·47 (0·03)	C(18)—C(23)	1·46 (0·03)
C(15)—C(16)	1·54 (0·03)	C(19)—C(20)	1·37 (0·03)
C(24)—C(25)	1·60 (0·04)	C(20)—C(21)	1·47 (0·03)
average value 1·55 Å		C(21)—C(22)	1·31 (0·04)
		C(22)—C(23)	1·43 (0·03)
		average value 1·41 Å	

Fig. 3. Bond lengths (Å).

The planarity of each ring and the perpendicular distances of the atoms from the least-squares planes can be seen in Table 5. The aglycone of the molecule consists of a fused system of six-, five- and four-membered rings forming a cage-like structure. The six-membered ring formed by the atoms C(1)~C(5) and C(7) takes a distorted half-boat conformation, in which the atoms C(3), C(4), C(5) and O(4) lie in a plane. The Br atom is attached to this ring in the axial direction as was discussed above.

The atoms C(1), C(6), C(5) and C(7) comprising the four-membered ring deviate from the mean plane alternately upwards and downwards by about 0·17 Å. This clearly indicates the puckered conformation. The angle between the normals of the two planes formed by C(1), C(5), C(6) and C(1), C(5), C(7) is 34° 19' and that between C(1), C(6), C(7) and C(5), C(6), C(7) is 35° 54'. These values agree well with those observed in the four-membered ring of 2-chlorotropone-cyclo-heptatriene adduct (Fukazawa, Itô & Iitaka, 1969).

The five-membered ring formed by C(1), C(2), O(2), C(9) and C(6) takes roughly an envelope form.

The glucose ring takes, as usual, a chair conformation, all substituents being oriented in the equatorial direction, so that the glucosyl group takes a so-called C1 form.

Four atoms comprising each acetoxyl group lie in a plane which is nearly perpendicular to the mean plane of the glucose ring except for the acetoxyl group attached to C(16). Thus the acetoxyl O–C bonds, O(7)–C(26), O(8)–C(28) and O(9)–C(30) take approximately eclipsed conformation with respect to the corresponding C–H bonds of the glucose ring, C(12)–H, C(13)–H and C(14)–H, while the bond C(16)–O(10) is staggered with respect to C(15)–H.

The atoms C(18), C(17), O(11) and O(5) of the benzoyl-oxy group lie nearly on a plane which makes an angle of only 2° 36' with that of the benzene ring.

The two bulky moieties, the glucosyl and benzoyl groups, are extended from the pinane skeleton in opposite directions to avoid intramolecular interactions. The conformation of the bonds at each junction of the moieties to the pinane skeleton is such that O(1)–C(11) adopts a nearly eclipsed conformation with respect to C(1) C(7), while C(8)–O(5) to C(6)–C(1) is a *trans* conformation. As a consequence of these particular conformations, the molecule takes the fully extended form and the mean planes of the glucosyl and benzoyl groups lie roughly on (100), which makes possible to stack the neighbouring molecules in [100].

The projection of the crystal structure along the c axis is shown in Fig. 5. In this figure, the shortest intermolecular distances less than or equal to 3·6 Å, from molecule I to the surrounding molecules, are shown by broken lines. The molecules are designated by the molecular number specifying the equivalent positions in the unit cell and also by the subscript in parentheses denoting the translations along the three edges of the cell. The equivalent positions are: I at x,y,z, II at $\frac{1}{2}-x, -y, -\frac{1}{2}+z$, III at $\frac{1}{2}+x,\frac{1}{2}-y, -z$ and IV at $-x,\frac{1}{2}+y,\frac{1}{2}-z$ where x, y, and z are the coordinates given in Table 1. Although the molecules possess an awkward structure, there is no peculiar feature in the packing of the molecules. They seem to be packed together mainly through van der Waals forces between acetyl and benzoyl groups.
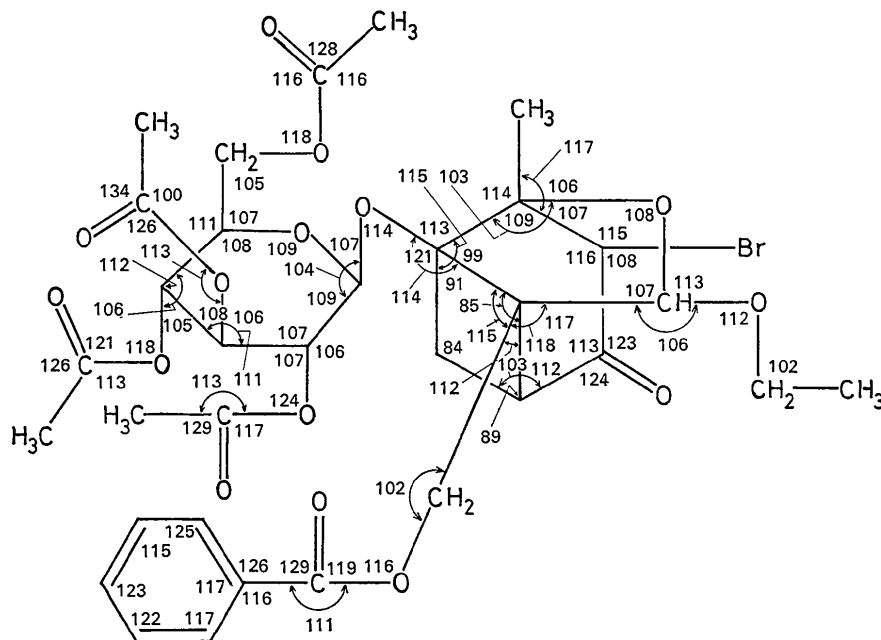
Fig. 4. Bond angles (°).

Table 5. *Deviations of the atoms from the least-squares planes*

The planes are of the form $AX + BY + CZ = D$, where X, Y, Z and D are in Å units relative to the axes a, b and c.

Plane forming atoms and distances from the plane		Distances from the plane		Coefficients of the equation of the plane	
Pinane skeleton					
Five-membered ring containing acetal group					
C(1)	−0·208 Å			A	0·741
C(2)	0·254			B	0·208
O(2)	−0·192			C	−0·639
C(9)	0·040			D	−8·721
C(6)	0·105				
Four-membered ring					
C(1)	−0·174			A	0·237
C(6)	0·172			B	−0·380
C(5)	−0·170			C	0·894
C(7)	0·171			D	13·774
Six-membered ring					
C(1)	−0·257	O(4)	0·110 Å	A	0·237
C(2)	−0·172			B	0·959
C(3)	0·338			C	0·082
C(4)	−0·042			D	1·739
C(5)	−0·504				
C(7)	0·637				
Ketone group					
C(3)	0·009	C(2)	−0·332	A	0·421
C(4)	−0·029	Br	1·696	B	0·825
C(5)	0·009	C(6)	−0·997	C	0·377
O(4)	0·012	C(7)	1·225	D	5·914
Acetyl groups					
C(26)	0·030 Å	C(12)	−0·020	A	−0·042
C(27)	−0·009			B	0·248
O(7)	−0·009			C	0·968
O(12)	−0·011			D	17·890
C(28)	0·015	C(13)	0·130	A	0·196
C(29)	−0·004			B	0·959
O(13)	−0·007			C	0·205
O(8)	−0·004			D	5·090
C(30)	−0·000	C(14)	0·086	A	−0·278
C(31)	−0·000			B	−0·791
O(14)	0·000			C	0·546
O(9)	0·000			D	8·198
C(32)	0·033	C(16)	0·032	A	0·648
C(33)	−0·011			B	0·315
O(10)	−0·010			C	0·694
O(15)	−0·013			D	13·992
Benzoyl group					
Carbonyl group					
C(17)	0·034 Å	C(8)	−0·116	A	0·936
O(5)	−0·010			B	0·267
O(11)	−0·013			C	0·231
C(18)	−0·011			D	4·645
Benzene ring					
C(18)	−0·042	C(17)	0·004	A	0·936
C(19)	0·026			B	0·301
C(20)	0·000			C	0·184
C(21)	−0·008			D	3·762
C(22)	−0·010				
C(23)	0·034				

Fig. 5. Projection of the crystal stiucture along the c axis. Intermolecular short contacts less than 3·6 Å (4·0 Å where they involve the bromine atom) are shown by broken lines.

work. Thanks are due to the staff of C. Itoh Electronic Computing Service Co Ltd for making the CDC 3600 and 6600 computers available to us. This work was supported by a Research Grant from the Ministry of Education.

References

Aimi, N., Inaba, M., Watanabe, M. & Shibata, S. (1969). *Tetrahedron*, **25**, 1825.

Corey, E. J. & Sneen, R. A. (1956). *J. Amer. Chem. Soc.* **78**, 6269.

Dauben, C. H. & Templeton, D. H. (1955). *Acta Cryst.* **8**, 841.

Fukazawa, Y., Itô, S. & Iitaka, Y. (1969). *Acta Cryst.* **B25**, 665.

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

Lentz, P. J. & Rossmann, M. G. (1969). *Chem. Commun.* p. 1269.

Masaki, N., Hirabayashi, M., Fuji, K., Osaki, K. & Inouye, H. (1967). *Tetrahedron Letters*, p. 2367.

Shibata, S. & Nakahara, M. (1963). *Chem. Pharm. Bull.* (*Tokyo*), **11**, 372.

Shibata, S., Nakahara, M. & Aimi, N. (1963), *Chem. Pharm. Bull.* (*Tokyo*), **11**, 379.

Shibata, S., Nakahara, M. & Aimi, N. (1964). *Tetrahedron Letters*, p. 1991.