2·750 (3), O(3)—H(O3) = 0·86 (3) Å, O(3)—H(O3)···O(4) = 170 (1)°. In (4a), hydroxyl H atoms for one molecule were located in difference maps, but those for the second molecule were not found. Two hydrogen bonds and one short O···O distance are noted: O(2')···O(3) = 2·801 (6); O(2')···H(O2)($-1 + x$, y, z) = 1·97 (8), O(2')···O(2) = 2·817 (6), O(2)—H(O2) = 0·99 (8) Å, O(2')···H(O2)—O(2) = 143 (2)°; O(3')···H(O1)($2 - x$, $1 - y$, $1 - z$) = 2·26 (8), O(3')···O(1) = 2·989 (6), O(1)—H(O1) = 0·75 (7) Å, O(3')···H(O1)—O(1) = 165 (2)°.

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Structure of Synthetic Bromobeckerelide. A Case of Diastereomeric Selection in the Solid State

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Abstract. 4-Bromo-5-hydroxy-3-(1-hydroxybutyl)-5-methyl-5H-furan-2-one, $C_9H_{13}BrO_4$, recrystallized from CH_2Cl_2/hexane, m.p. 359–360 K, $M_r = 265·1$, triclinic, $P\bar{1}$, $a = 5·9067 (4)$, $b = 9·4807 (9)$, $c = 11·0895 (11)$ Å, $\alpha = 74·16 (1)$, $\beta = 79·96 (1)$, $\gamma = 71·87 (1)°$, $V = 565·1 (1)$ Å^3, $Z = 2$, $F(000) = 268$, $D_x = 1·56$ Mg m^{-3}, λ(Mo $K\alpha$) = 0·71069 Å, $\mu = 3·59$ mm^{-1}, room temperature, $R = 0·044$ [$wR = 0·043$, $w = 1/\sigma^2(F_o)$] for 1273 observed reflections [$|F_o| > 4\sigma(F_o)$]. In the solid state, which is different from the situation in solution, only the diastereomer having the like configuration is observed. Molecules of the same configuration are linked by hydrogen bonds involving both hydroxyl groups of the same molecule.

Introduction. Bromo- and chlorobeckerelide [(1) and (2)] were isolated as an inseparable 10:1 mixture from the red marine alga *Beckerella subcostatum* collected near Kozu island, Japan. The unusual structure and potent antimicrobial activity of (1) and (2), which were reported some 12 years ago (Ohta, 1977), have generated considerable interest. Despite various approaches, the synthesis of the major constituent (1) has only been recently accomplished (Jefford, Jaggi & Boukouvalas, 1989), thereby

making available the chemically pure compound for the first time.

(1) X = Br
(2) X = Cl
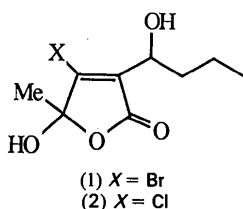
In solution, only a single time-averaged structure is observed by ^{1}H NMR (360 MHz, CDCl$_3$ at 213 to 298 K or in C$_6$D$_6$ at 298 K) for bromobeckerelide (1), which corresponds to the rapid interconversion of diastereomers (3) and (5). Treatment of (1) with excess Ac$_2$O in pyridine for 4 h at 298 K captured (3) and (4) to give the diacetates (6) and (7) in a 1:1 ratio (yield = 97%), which were identified by the two signals observed for the methyl substituent at the anomeric C(3) atom (δ 1·66 and 1·68). In another experiment, bromobeckerelide (1) was treated with excess CH$_2$N$_2$ in ether for 1 h at 298 K to give the keto ester (8) in 55% yield after purification. Clearly, the formation of (8) proves that the open-chain carboxylic acid (4) is the intermediate common to (3) and (5). These findings fully support the equilibrium (3)⟷(4)⟷(5) and are compatible with previous observations of related hydroxybutenolides (Kikuchi, Tsukitani, Nakanishi, Shimizu, Saitoh, Iguchi & Yamada, 1983). Moreover, the acid (4) must be present, but only in trace amounts since it cannot be observed by ^{1}H NMR, while the lactones (3) and (5) exist in equal amounts. When (1) is examined in the solid state, it is found that the foregoing equilibrium is completely displaced towards (3). Determination of the structure of (1) confirms that it exists as (3) and also reveals that intermolecular hydrogen bonding is responsible for this predilection.

(3)   (4)   (5)

(6)   (8)   (7)
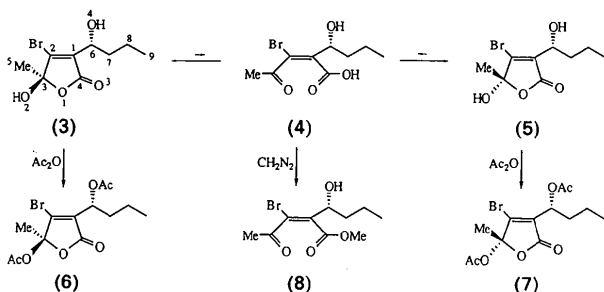
Experimental. Single crystals of (3) were grown at room temperature from CH$_2$Cl$_2$/hexane solution. Lattice parameters were refined from 26 reflections ($21 < 2\theta < 31°$) on a Nonius CAD-4 diffractometer, using graphite-monochromated Mo $K\alpha$ radiation ($\lambda = 0·71069$ Å). Data were collected at room tempera-

Table 1. *Fractional coordinates and equivalent isotropic atomic displacement parameters for bromo-beckerelide (3) with e.s.d.'s in parentheses*

	x	y	z	U_{eq}
Br	0·7720 (1)	0·29357 (9)	0·58412 (6)	0·080 (1)
O(1)	0·6647 (6)	0·2315 (4)	0·9668 (3)	0·052 (4)
O(2)	0·4231 (7)	0·1901 (5)	0·8427 (4)	0·060 (4)
O(3)	0·7972 (8)	0·4046 (5)	1·0151 (4)	0·071 (5)
O(4)	1·1586 (7)	0·4856 (5)	0·7845 (4)	0·056 (4)
C(1)	0·8189 (9)	0·3913 (6)	0·7981 (4)	0·041 (5)
C(2)	0·7567 (9)	0·2987 (6)	0·7527 (4)	0·044 (5)
C(3)	0·653 (1)	0·1823 (6)	0·8530 (5)	0·045 (5)
C(4)	0·762 (1)	0·3485 (7)	0·9371 (5)	0·050 (6)
C(5)	0·805 (1)	0·0203 (8)	0·8661 (7)	0·065 (7)
C(6)	0·938 (1)	0·5164 (7)	0·7349 (5)	0·048 (6)
C(7)	0·779 (1)	0·6765 (7)	0·7378 (6)	0·054 (6)
C(8)	0·570 (1)	0·7273 (8)	0·6627 (7)	0·070 (8)
C(9)	0·408 (2)	0·884 (1)	0·6689 (8)	0·10 (1)
H(O2)	0·333 (9)	0·286 (6)	0·828 (5)	0·05
H(O4)	1·15 (1)	0·509 (7)	0·844 (5)	0·05
H(51)	0·801 (9)	−0·003 (6)	0·791 (5)	0·05
H(52)	0·745 (8)	−0·049 (6)	0·939 (5)	0·05
H(53)	0·964 (9)	0·023 (6)	0·874 (4)	0·05
H(6)	0·980 (9)	0·510 (6)	0·657 (5)	0·05
H(71)	0·873 (8)	0·753 (6)	0·700 (4)	0·05
H(72)	0·716 (8)	0·684 (6)	0·821 (5)	0·05
H(81)	0·643 (8)	0·728 (6)	0·576 (5)	0·05
H(82)	0·478 (9)	0·663 (6)	0·689 (4)	0·05
H(91)	0·358 (9)	0·890 (6)	0·749 (5)	0·05
H(92)	0·505 (9)	0·943 (6)	0·632 (5)	0·05
H(93)	0·284 (9)	0·920 (6)	0·614 (4)	0·05

Table 2. *Selected interatomic distances (Å), bond angles (°) and torsional angles (°) with e.s.d.'s in parentheses for bromobeckerelide (3)*

Br—C(2)	1·869 (5)	C(1)—C(4)	1·488 (7)
O(1)—C(3)	1·477 (7)	C(1)—C(6)	1·512 (9)
O(1)—C(4)	1·343 (8)	C(2)—C(3)	1·530 (7)
O(2)—C(3)	1·363 (8)	C(3)—C(5)	1·500 (8)
O(3)—C(4)	1·207 (9)	C(6)—C(7)	1·522 (8)
O(4)—C(6)	1·419 (8)	C(7)—C(8)	1·489 (10)
C(1)—C(2)	1·291 (9)	C(8)—C(9)	1·511 (11)

C(3)—O(1)—C(4)	111·0 (4)	Br—C(2)—C(3)	117·9 (5)
C(2)—C(1)—C(4)	106·4 (5)	C(1)—C(2)—C(3)	113·7 (5)
C(2)—C(1)—C(6)	131·3 (5)	O(1)—C(4)—O(3)	122·9 (5)
C(4)—C(1)—C(6)	122·3 (6)	O(1)—C(4)—C(1)	109·3 (5)
Br—C(2)—C(1)	128·4 (4)	O(3)—C(4)—C(1)	127·8 (6)

C(2)—C(1)—C(6)—O(4)	−119·9 (6)	C(4)—C(1)—C(6)—C(7)	−70·5 (7)
C(2)—C(1)—C(6)—C(7)	113·0 (7)	C(1)—C(6)—C(7)—C(8)	−66·3 (7)
C(4)—C(1)—C(6)—O(4)	56·6 (6)	C(6)—C(7)—C(8)—C(9)	178·3 (6)

ture using a crystal ca $0·14 \times 0·20 \times 0·37$ mm with $\omega/2\theta$ scans $[\Delta\theta = (1·2 + 0·35\tan\theta)°]$, two standard reflections measured every 100 reflections. Of 1369 Friedel pairs measured for $2 < 2\theta < 44°$ and $\pm h(6)$, $\pm k(9)$ $+ l(11)$, 1273 with $|F_o| > 4\sigma(F_o)$ were used in the refinement; Lorentz–polarization, no absorption or secondary-extinction corrections; structure solved by *MULTAN*87 (Main, Fiske, Hull, Lessinger, Germain, Declercq & Woolfson, 1987). Full-matrix least-squares refinement using $|F|$ values. Scattering factors from Cromer & Mann (1968), and anomalous-dispersion corrections from *International Tables for X-ray Crystallography* (1974). All coordinates of H atoms were observed and refined with a

fixed value of isotropic displacement parameters. The final residuals were $R = 0.044$, $wR = 0.043$ [$w = 1/\sigma^2(F_o)$]; $S = 4.00$. 166 parameters were refined, average and max. $\Delta/\sigma = 0.027$ and 0.30 [for H(O2) atom]; max. and min. $\Delta\rho = 0.67$ and -0.61 e Å^{-3}. All calculations performed with $XTAL$ (Hall & Stewart, 1987).

Discussion. Final positional parameters are given in Table 1.* Selected bond distances, valence angles and torsional angles are reported in Table 2. As the synthesis of (3) (Jefford, Jaggi & Boukouvalas, 1989) is non-stereoselective at the C(3) and C(6) atoms, enantiomeric pairs of both diastereomers are formed. In other words, in addition to the diastereomeric pairs (3) and (5), which possess the C(3)R,C(6)R (like) and C(3)S,C(6)R (unlike) configurations respectively (Seebach & Prelog, 1982), there are also the pairs (3') and (5') (not shown) in which the configurations are enantiomeric. What the X-ray structure reveals (Fig. 1) is that only the like forms, (3) and (3'), having configurations C(3)R,C(6)R and C(3)S,C(6)S, are present in the solid state.

It is worth noting that the two substituents at the anomeric C(3) atom are clearly distinguishable. The relative configuration C(3)R,C(6)R is correct for several reasons. (i) The observed bond lengths [C(3)—C(5) = 1.500 (8) and C(3)—O(2) = 1.363 (8) Å] are in good agreement with the standard values observed for C—C_{methyl} and C—$O_{hydroxyl}$ dis-

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* Lists of structure factors, atomic positional and anisotropic displacement parameters for all atoms, and other information in the printed form of the Standard Crystallographic File Structure of Brown (1985) have been deposited with the British Library Document Supply Centre as Supplementary Publication No. SUP 52886 (18 pp.). Copies may be obtained through The Technical Editor, International Union of Crystallography, 5 Abbey Square, Chester CH1 2HU, England.

tances respectively. (ii) The ring hydroxyl group of one molecule is involved as donor in a hydrogen bond with the O(4) atom of another molecule and the relevant interatomic distance is O(2)$\cdots$O(4)($x - 1$, y, z) = 2.710 (5) Å. Moreover, the H atoms of both the hydroxyl and methyl groups are clearly visible on the difference electron density map, permitting their positions to be refined. The resulting geometry can be considered as satisfactory. (iii) The refinement of the anisotropic displacement parameters does not lead to abnormal values of the tensor associated with these atomic sites.

The hydroxyl group at C(6) is also implicated in an intramolecular hydrogen bond with the carbonyl [O(4)$\cdots$O(3) = 3.120 (5) Å, O(4)—H(O4)$\cdots$O(3) = 109 (5)°] so that the lateral chain [O(4), C(6) to C(9)] adopts an all-*trans* conformation. The five atoms of the butenolide ring are disposed in a mean plane with a maximum deviation of 0.011 Å for C(4). The distribution of bond lengths around O(1) is clearly asymmetric as found in analogous lactones (Merlino, 1971; Fenske, Prokscha, Stock & Becher, 1980; Lere-Porte & Petrissans, 1981). The molecular packing is formed by chains of molecules linked by hydrogen bonds (Fig. 1) and no short interactions are observed between the chains. A further point is that only arrays of molecules of like configuration are bound by hydrogen bonds. There is no racemic association.

It can be concluded that the formation of (3) or (3') to the detriment of (5) and (5') can be attributed to the greater strength of the resulting hydrogen bonds, thereby leading to an energetically more stable crystal.
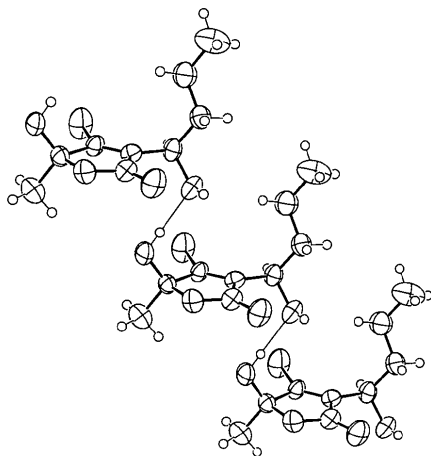

Fig. 1. Perspective view of bromobeckerelide (3) showing hydrogen bonds in the molecular packing.

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