95. X-Ray Structure Analysis of 15-Apoviolaxanth-15-al

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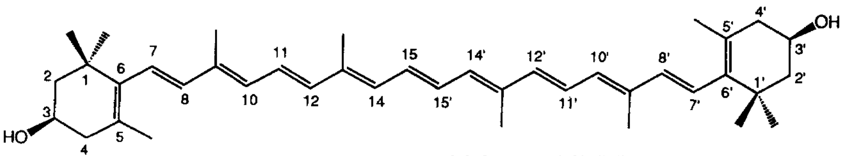
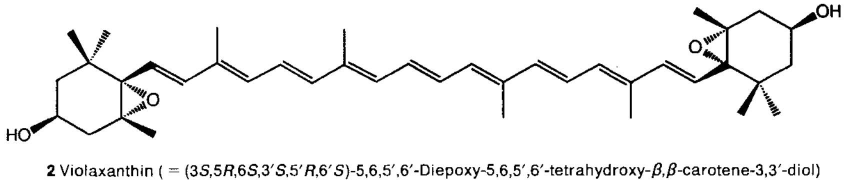
The X-ray structure of 15-apoviolaxanth-15-al (= (1′*S*,2′*R*,4′*S*,2*E*,4*E*,6*E*,8*E*)-9-(1′,2′-epoxy-4′-hydroxy-2′,6′,6′-trimethylcyclohexyl)-3,7-dimethylnona-2,4,6,8-tetraenal) is reported. The four symmetry-independent molecules in the asymmetric unit are linked into X-shaped spirals by intermolecular H-bonds. Additional H-bonds interconnect the spirals, forming wave-like chains. The geometry of the polyene side chain possesses the same in-plane bending observed for related retinal and carotenoid compounds. The polyene side chain deviates from planarity by twists of up to 10° about each bond; some of the largest twists are about C=C bonds. The epoxycyclohexane ring possesses a distorted 'C(3)-sofa' conformation. The torsion angles about the bond connecting the polyene chain to the cyclohexane ring are compared with equivalent torsion angles in molecules containing epoxide rings substituted with a π-system in order to examine possible interactions between the epoxide group and the π-system, either through pseudoconjugation, or through an interaction of the nonbonding orbitals of the epoxy O-atom with the π-orbitals of the polyene chain. The latter is considered to be more likely.

1. Introduction. – The biological conversion of zeaxanthin (**1**) into violaxanthin (**2**) is accompanied by a dramatic change in chemical and spectroscopic properties. Not only is the sensitivity to acids very much enhanced in the epoxidic violaxanthin, but there is a marked increase in the propensity of **2** to undergo molecular rearrangements[1]). Moreover, the circular dichroism (CD) of **2** is distinctly different, both quantitatively and qualitatively, from that of **1** (*Fig. 1*).



1 Zeaxanthin (= (3*R*,3′*R*)-*β*,*β*-Carotene-3,3′-diol)



2 Violaxanthin (= (3*S*,5*R*,6*S*,3′*S*,5′*R*,6′*S*)-5,6,5′,6′-Diepoxy-5,6,5′,6′-tetrahydroxy-*β*,*β*-carotene-3,3′-diol)

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[1]) A summary of important rearrangements is given in [1].

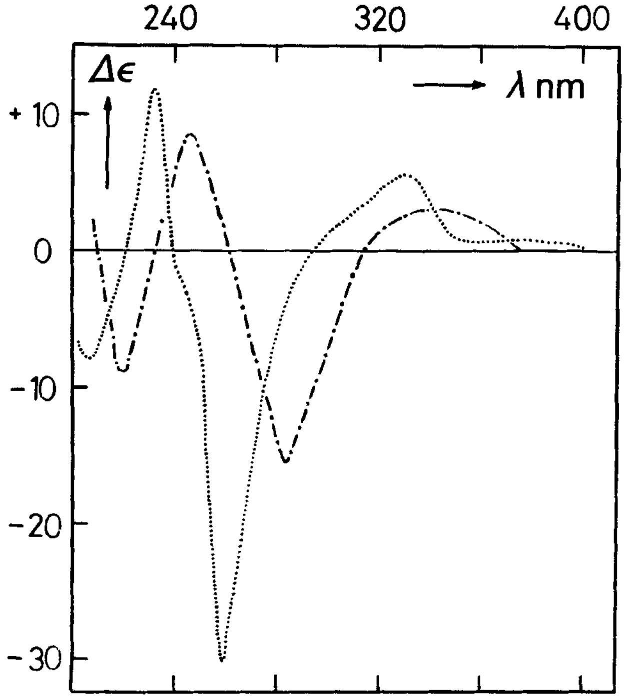

Fig. 1. *CD Spectra of zeaxanthin* (**1**–·–·–·) *and violaxanthin* (**2**·····), *redrawn after* [2] [3]

Satisfactory explanations have been put forward for the acid lability of violaxanthin[2]) as well as for some of the rearrangements; however, the changes in CD properties have not yet been rationalised. It is evident that the immediate proximity of the chiral centres at C(6,6′) to the polyene chain strongly influences the *Cotton* effect, but the intrinsic nature of these chiral centres and the influence of the torsion angles, C(1)–C(6)–C(7)–C(8) (ω_1) and C(1′)–C(6′)–C(7′)–C(8′) (ω'_1), on the CD spectra are not known. As yet, there are no reported X-ray structure analyses of either **1** or **2**[3]). According to the CD models of *Noack* and *Thompson* [8], and *Sturzenegger et al.* [9], the torsion angle, ω_1, plays an important role in determining the shape of the *Cotton* curve.

The present paper presents the details of the X-ray structure determination of 15-apoviolaxanth-15-al (=(1′*S*,2′*R*,4′*S*,2*E*,4*E*,6*E*,8*E*)-9-(1′,2′-epoxy-4′-hydroxy-2′,6′,6′-trimethylcyclohexyl)-3,7-dimethylnona-2,4,6,8-tetraenal) (**3**)[4]). The conformation of the violaxanthin end group will be compared with the results of earlier calculations made for (9′*Z*)-neoxanthin (**4**) [11] (see *Chapt. 5*). Also to be discussed is the possible interaction of the epoxide group with the polyene chain, either through pseudoconjugation [12], or through an interaction of the nonbonding orbitals of the epoxy O-atom with the π-orbitals of the polyene chain (see *Chapt. 6*).

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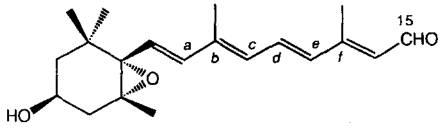
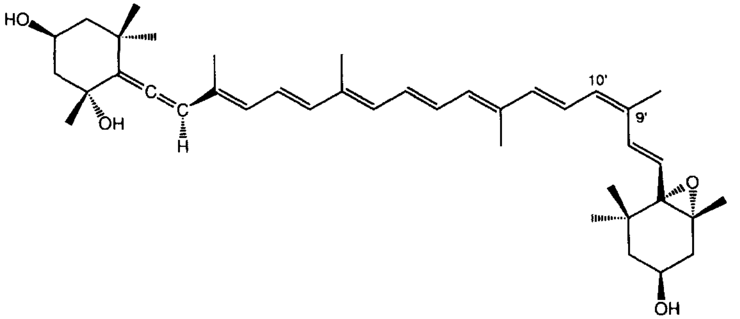
[2]) For the earliest rudimentary mechanism, see [4], and for modified versions, see [5] [6].

[3]) For the X-ray structure of the zeaxanthin end group in capsanthin, see [7] and *Chapt. 7*.

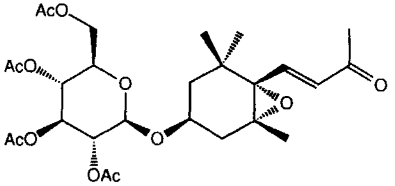
[4]) For the synthesis and absolute configuration of **3**, see [10].



3 15-Apoviolaxanth-15-al
(= (1'*S*,2'*R*,4'*S*,2*E*,4*E*,6*E*,8*E*)-9-(1',2'-Epoxy-4'-hydroxy-2',6',8'-trimethylcyclohexyl)-3,7-dimethylnona-2,4,6,8-tetraenal)



4 (9'*Z*)-Neoxanthin (= (3*S*,5*R*,6*R*,3'*S*,5'*R*,6'*S*,9'*Z*)-5',6'-Epoxy-6,7-didehydro-5,6,5',6'-tetrahydro-*β*,*β*-carotene-3,5,3'-triol)



5 3,3,5-Trimethyl-4-(3-oxobut-1-enyl)-4,5-epoxycyclohexyl 2,3,4,6-tetra-*O*-acetyl-*β*-D-glucopyranoside

2. Crystal-Structure Determination of 3. – Crystals of **3**, obtained by diffusion of acetone and hexane solutions, were used for the X-ray structure determination. The intensities were collected on a *Nicolet R3* diffractometer using graphite-monochromated MoK_α radiation (λ = 0.71069 Å) and *Wyckoff* ω scans. Three standard reflections measured every 150 reflections showed negligible variation in intensity. The intensities were corrected for *Lorentz* and polarization effects, but not for absorption. The structure was solved by direct methods using SHELXS86 [13], which revealed the positions of all non-H-atoms. There are four symmetry independent molecules in the asymmetric unit. The atomic coordinates of the four molecules were tested carefully for a relationship from a higher-symmetry space group using the MISSYM routine [14] of the program PLATON [15], but none could be found. All of the H-atoms, except those belonging to the OH groups, were placed in idealised positions (d(C–H) = 0.95 Å) with fixed isotropic temperature factors calculated as 1.2B_{eq} of the C-atom to which each was bonded. Only three of the four OH H-atoms could be located in a difference electron-density map. Anisotropic refinement of the non-H-atoms and isotropic refinement of the three located OH H-atoms were carried out on F using full-matrix least-squares procedures, which minimized the function $\Sigma w(|F_o| - |F_c|)^2$. Corrections for secondary extinction were not applied. The absolute configuration was not determined; the enantiomorph chosen for the refinement was based on the known configuration of the precursor to **3**. All calculations were performed with the TEXSAN crystallographic software package [16]. Data

Table 1. *Crystallographic Data for* **3**

Empirical formula	$C_{20}H_{28}O_3$	D_x [g cm^{-3}]	1.126
Formula weight	316.44	Absorption coefficient μ (MoK_α) [cm^{-1}]	0.690
Crystal colour, habit	golden yellow, prism		
Crystal dimensions [mm]	0.24 × 0.45 × 0.60	$2\theta_{max}$ [°]	50
Temperature [K]	213 (1)	Total reflections measured	8042
Crystal system	orthorhombic	Symmetry-independent reflections	7885
Space group	$P2_12_12_1$		
Reflections for cell determination	25	Observed reflections [$I > 2\sigma(I)$]	4147
2θ range for cell determination [°]	22–28	Variables	842
		Final R	0.069
a [Å]	7.949 (1)	R_w	0.067
b [Å]	21.855 (3)	Weights w	$[\sigma^2(F_o)+(0.00063F_o)^2]^{-1}$
c [Å]	42.983 (5)	Goodness of fit s	1.510
V [Å^3]	7467 (2)	Final Δ_{max}/σ	0.014
Z	16	$\Delta\rho$ (max; min) [e Å^{-3}]	0.29; −0.29

collection and refinement parameters are listed in *Table 1*[5]). The reflection/parameter ratio is quite small, because of the large number of atoms in the asymmetric unit, and the modest diffracting power of the crystal. As a result, the estimated standard deviations of the atomic coordinates and, thus, of the bond lengths and angles are slightly larger than normally observed for organic structures.

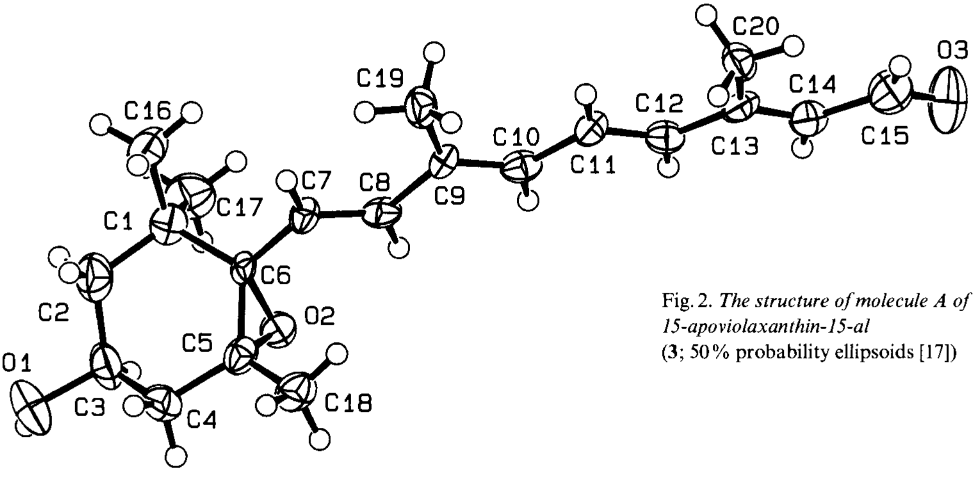


Fig. 2. *The structure of molecule A of 15-apoviolaxanthin-15-al*
(**3**; 50% probability ellipsoids [17])

3. General Description of the Structure. – A view of molecule A of **3**, which is representative of all of the independent molecules, is shown in *Fig. 2*. The configuration of the polyene side chain is all-*E*, and the orientation of the C(7)=C(8) bond with respect to the epoxy O-atom is *syn*. The primary unusual feature of the structure of **3** is that there are four independent molecules in the asymmetric unit. The main reason for this is probably

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[5]) Atomic coordinates, bond lengths, and bond angles have been deposited with the *Cambridge Crystallographic Data Centre*, 12 Union Road, Cambridge CB2 1EZ, England.

the asymmetric nature of the H-bonding interactions, which will be discussed below. The bond lengths and angles of the four molecules show no significant differences and the mean values are given in *Table 2*. The torsion angles (*Table 3*) also show that the molecules are very similar geometrically. With the exception of the torsion angles within the polyene side chain, and, in particular, those about the C(6)–C(7) bond, the differences between the torsion angles for the respective molecules are almost all within the limits of uncertainty of the angles, with the maximum range for any one angle being 7°. The torsion angles about the C(6)–C(7) bond show variations of up to 23°, while the other torsion angles within the polyene side chain exhibit smaller variations, with a maximum difference of 14°. These differences in geometry between the independent molecules are most probably caused by crystal packing, since the long polyene chain will be most heavily influenced by the packing requirements within the crystal lattice. The differences are not considered to be significant in terms of the chemistry or electronic interactions within the molecule.

Table 2. *Mean Bond Lengths* [Å] *and Bond Angles* [°] *for the Four Independent Molecules of* **3** *with Estimated Standard Deviations in Parentheses*

O(1)–C(3)	1.43(1)	C(2)–C(3)	1.50(1)	C(9)–C(10)	1.35(1)
O(2)–C(5)	1.45(1)	C(3)–C(4)	1.50(1)	C(9)–C(19)	1.50(1)
O(2)–C(6)	1.449(9)	C(4)–C(5)	1.51(1)	C(10)–C(11)	1.43(1)
O(3)–C(15)	1.22(1)	C(5)–C(6)	1.48(1)	C(11)–C(12)	1.34(1)
C(1)–C(2)	1.53(1)	C(5)–C(18)	1.49(1)	C(12)–C(13)	1.46(1)
C(1)–C(6)	1.55(1)	C(6)–C(7)	1.47(1)	C(13)–C(14)	1.35(1)
C(1)–C(16)	1.52(1)	C(7)–C(8)	1.33(1)	C(13)–C(20)	1.50(1)
C(1)–C(17)	1.52(1)	C(8)–C(9)	1.45(1)	C(14)–C(15)	1.44(1)

C(5)–O(2)–C(6)	61.1(5)	O(2)–C(6)–C(5)	59.6(5)
C(2)–C(1)–C(6)	111.1(7)	O(2)–C(6)–C(7)	113.2(7)
C(2)–C(1)–C(16)	108.3(8)	C(1)–C(6)–C(5)	121.1(7)
C(2)–C(1)–C(17)	110.1(8)	C(1)–C(6)–C(7)	115.5(7)
C(6)–C(1)–C(16)	109.6(7)	C(5)–C(6)–C(7)	119.9(7)
C(6)–C(1)–C(17)	109.0(7)	C(6)–C(7)–C(8)	125.0(8)
C(16)–C(1)–C(17)	108.7(7)	C(7)–C(8)–C(9)	127.1(8)
C(1)–C(2)–C(3)	116.9(8)	C(8)–C(9)–C(10)	119.3(8)
O(1)–C(3)–C(2)	111.2(8)	C(8)–C(9)–C(19)	118.1(7)
O(1)–C(3)–C(4)	109.5(8)	C(10)–C(9)–C(19)	122.6(8)
C(2)–C(3)–C(4)	109.7(8)	C(9)–C(10)–C(11)	128.8(8)
C(3)–C(4)–C(5)	113.4(8)	C(10)–C(11)–C(12)	123.9(8)
O(2)–C(5)–C(4)	113.1(7)	C(11)–C(12)–C(13)	127.2(8)
C(2)–C(5)–C(6)	59.3(5)	C(12)–C(13)–C(14)	118.4(8)
O(2)–C(5)–C(18)	114.6(8)	C(12)–C(13)–C(20)	118.2(8)
C(4)–C(5)–C(6)	120.5(8)	C(14)–C(13)–C(20)	123.3(8)
C(4)–C(5)–C(18)	114.9(8)	C(13)–C(14)–C(15)	126.7(9)
C(6)–C(5)–C(18)	121.1(8)	O(3)–C(15)–C(14)	123.1(9)
O(2)–C(6)–C(1)	113.7(7)		

The OH groups facilitate the formation of H-bonds, all of which are intermolecular interactions. *Fig. 3* shows the packing of the molecules in the unit cell and their interconnection by H-bonding. The four independent molecules are linked into a tetrameric sequence, D→A→C→B, by H-bond donation to the O-atom of the OH group of a neighbouring molecule. These four molecules form an X-shaped spiral pattern with the OH groups being stacked on top of one another and all pointing to the centre of the X. Molecule B does not continue the spiral by further donation to the OH group of another molecule D, but instead donates to the C=O O-atom of the tail of an adjacent molecule B.

Table 3. *Torsion Angles* [°] *for* **3** *with Estimated Standard Deviations in Parentheses*

	Molecule A	Molecule B	Molecule C	Molecule D
C(5)–O(2)–C(6)–C(1)	–113.1(8)	–113.7(8)	–112.9(9)	–113.8(9)
C(5)–O(2)–C(6)–C(7)	111.9(8)	111.3(8)	114.2(9)	111.3(9)
C(6)–O(2)–C(5)–C(4)	111.8(8)	113.0(8)	113.2(9)	113(1)
C(6)–O(2)–C(5)–C(18)	–113.5(8)	–113.0(8)	–113.3(9)	–112(1)
C(2)–C(1)–C(6)–O(2)	72.9(7)	71.9(7)	75.7(8)	74.1(8)
C(2)–C(1)–C(6)–C(5)	6.2(9)	4.9(9)	7(1)	5(1)
C(2)–C(1)–C(6)–C(7)	–153.2(6)	–155.2(6)	–151.7(7)	–152.0(7)
C(6)–C(1)–C(2)–C(3)	–35.6(9)	–36.2(9)	–40.8(9)	–37(1)
C(16)–C(1)–C(2)–C(3)	–157.1(7)	–157.3(7)	–163.4(7)	–156.6(8)
C(17)–C(1)–C(2)–C(3)	85.3(9)	85.1(8)	78.5(9)	82(1)
C(16)–C(1)–C(6)–O(2)	–167.7(6)	–169.7(5)	–164.7(6)	–166.7(7)
C(16)–C(1)–C(6)–C(5)	125.6(7)	123.3(7)	126.7(8)	124.9(9)
C(16)–C(1)–C(6)–C(7)	–33.7(8)	–36.7(8)	–32.1(9)	–32.9(9)
C(17)–C(1)–C(6)–O(2)	–49.8(8)	–50.8(7)	–45.7(8)	–47.0(9)
C(17)–C(1)–C(6)–C(5)	–116.5(7)	–117.8(7)	–114.2(8)	–115.3(9)
C(17)–C(1)–C(6)–C(7)	84.2(7)	82.1(8)	86.9(8)	86.8(9)
C(1)–C(2)–C(3)–O(1)	–179.8(6)	–177.7(5)	–175.9(7)	–176.3(6)
C(1)–C(2)–C(3)–C(4)	58.7(9)	63.5(8)	62.9(9)	60.2(9)
O(1)–C(3)–C(4)–C(5)	–171.6(6)	–177.2(6)	–170.4(7)	–173.8(7)
C(2)–C(3)–C(4)–C(5)	–49.4(9)	–55.6(8)	–49.6(9)	–49(1)
C(3)–C(4)–C(5)–O(2)	–44.8(8)	–40.7(8)	–47.2(8)	–45(1)
C(3)–C(4)–C(5)–C(6)	22.7(9)	26.4(9)	20(1)	21(1)
C(3)–C(4)–C(5)–C(18)	179.9(6)	–174.9(6)	179.9(7)	–179.6(8)
O(2)–C(5)–C(6)–C(1)	101.0(9)	99.7(9)	102(1)	101(1)
O(2)–C(5)–C(6)–C(7)	–100.5(9)	–100.7(9)	–101(1)	–102(1)
C(4)–C(5)–C(6)–O(2)	–101.6(6)	–100.6(6)	–99.8(6)	–99.6(7)
C(4)–C(5)–C(6)–C(1)	–0.6(9)	–0.9(9)	2(1)	1(1)
C(4)–C(5)–C(6)–C(7)	157.8(6)	158.8(6)	159.5(7)	158.4(7)
C(18)–C(5)–C(6)–O(2)	103.0(6)	102.2(6)	101.0(6)	101.9(8)
C(18)–C(5)–C(6)–C(1)	–156.0(6)	–158.1(6)	–156.9(7)	–157.1(8)
C(18)–C(5)–C(6)–C(7)	2.4(9)	1.6(9)	0(1)	0(1)
O(2)–C(6)–C(7)–C(8)	11(1)	16(1)	11(1)	32(1)
C(1)–C(6)–C(7)–C(8)	–123.6(8)	–116.9(8)	–121.6(9)	–101.5(9)
C(5)–C(6)–C(7)–C(8)	76.8(9)	82.6(9)	80(1)	100(1)
C(6)–C(7)–C(8)–C(9)	179.9(7)	179.6(7)	176.7(7)	–177.7(8)
C(7)–C(8)–C(9)–C(10)	179.6(7)	–174.3(7)	–172.1(7)	–177.9(7)
C(7)–C(8)–C(9)–C(19)	2(1)	5(1)	7(1)	3(1)
C(8)–C(9)–C(10)–C(11)	–173.7(7)	173.0(8)	173.4(8)	–173.3(8)
C(19)–C(9)–C(10)–C(11)	4(1)	–6(1)	–5(1)	6(1)
C(9)–C(10)–C(11)–C(12)	–179.8(7)	–177.5(7)	–174.7(7)	–179.7(7)
C(10)–C(11)–C(12)–C(13)	–173.6(7)	174.5(7)	172.5(7)	–171.1(8)
C(11)–C(12)–C(13)–C(14)	–176.4(7)	179.7(7)	–176.6(8)	–177.6(7)
C(11)–C(12)–C(13)–C(20)	2(1)	–1(1)	4(1)	3(1)
C(12)–C(13)–C(14)–C(15)	178.4(8)	179.3(8)	177.4(9)	178.0(8)
C(20)–C(13)–C(14)–C(15)	0(1)	–0(1)	–4(1)	–3(1)
C(13)–C(14)–C(15)–O(3)	–174.6(8)	170.5(8)	–176.8(9)	–175.3(8)

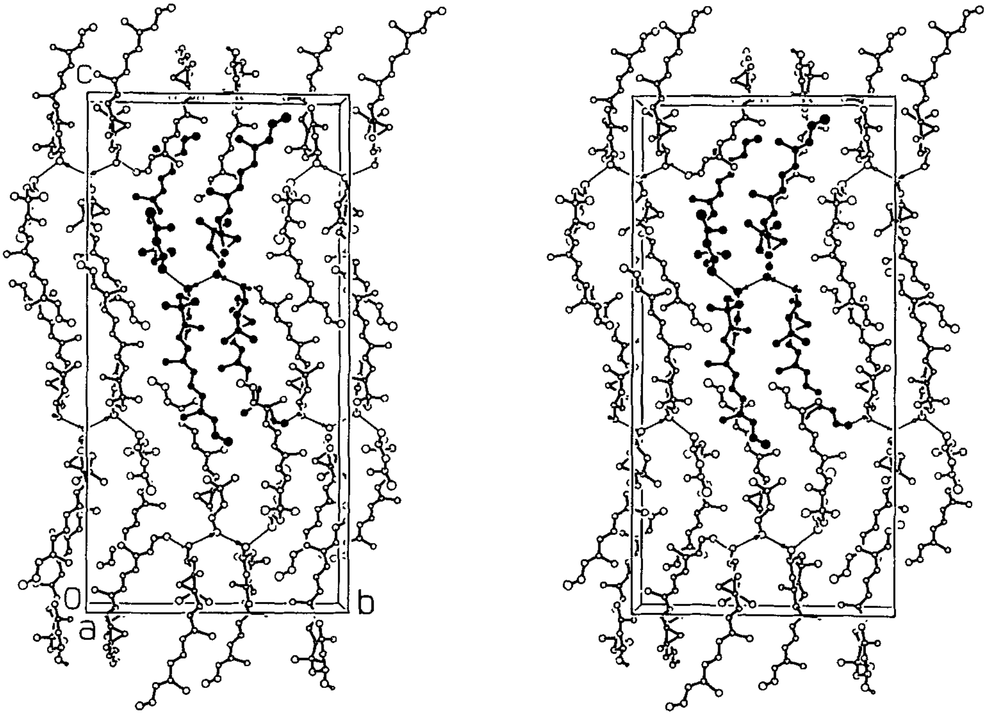

Fig. 3. *Stereoview of the molecular packing of* **3**, *projected down the* a-*axis*. The X-shaped tetrameric spiral is highlighted.

These interactions link the B molecules, and thus the individual tetrameric spirals, into infinite one dimensional wave-like chains which run parallel to the crystal x-axis. That there are four symmetry-independent molecules in the structure may, in part, be attributed to the asymmetrical pattern of the H-bonding interactions, which require the unique repeating unit within the crystal lattice to contain four molecules.

4. Conformation of the Polyene Side Chain. – The pattern of bond lengths within the polyene side chain of **3** corresponds with that normally observed for highly conjugated compounds of this type. The formal C=C bonds are in the range 1.33–1.35 Å and the intermediate formal single bonds are in the range 1.42–1.48 Å. The magnitudes of the estimated standard deviations for the bond lengths make it difficult to determine if there is a slight lengthening of the C=C bonds and shortening of the single bonds towards the middle of the chain, although the central single bond, C(10)–C(11), may be slightly shorter than the others. This property has been observed in related compounds and is attributed to the increased delocalisation of the π-bonds in the middle of the chain [18].

The conjugated polyene side chains show the typical sabre-like, in-plane bending observed for retinals and carotenoid compounds [18–20]. The chain angles for an unhindered conjugated chain are *ca.* 125° [21]. In **3**, the angles opposite the Me substituents are compressed to 117–120°, while the chain angles adjacent to the substituents are in the range 125–129°. This effect is the result of nonbonded interactions between the Me substituents on the chain and adjacent H-atoms. *Schenk* [19] defined an expression for the bending in such chains as $\Delta = a - b + c - d + e - f$, where the angles a–f are the chain angles associated with the atoms C(8)–C(13), respectively (see structural formula of **3** and *Fig. 2*). For the four independent molecules of **3**, the values of Δ are 21.1°, 22.9°, 18.6°, and 23.0°. These values are similar to those calculated from the structures of related (all-*E*)-polyenes.

The conjugated chains in **3** are not completely planar, as shown by the torsion angles about the bonds within the chain (*Table 3*). These deviations from planarity are caused by small twists about the bonds, with the maximum twist about any one bond being 10°. Contrary to the usual observations, some of the largest twists occur about the C=C bonds. *Table 4* shows the successively increasing angles between the four-atom planes along the chain and the plane defined by the atoms C(6)–C(7)–C(8)–C(9). Twists about the chain bonds can lead to both an out-of-plane bending and a longitudinal twisting of the chain. The out-of-plane curvature is most pronounced for molecule C, but barely detectable for molecules A and D. Out-of-plane bending has been noted for related carotenoid and retinal compounds, and is thought to be caused by intermolecular forces [21a] [22] [23].

Table 4. *Angles* [°] *between Four-Atom Planes of the Polyene Chain and the C(6)–C(7)–C(8)–C(9) Plane of* **3**

Plane	Molecule A	Molecule B	Molecule C	Molecule D
C(7)–C(8)–C(9)–C(10)	0.3	3.4	4.0	2.6
C(8)–C(9)–C(10)–C(11)	2.0	5.9	7.3	4.8
C(9)–C(10)–C(11)–C(12)	6.1	7.0	9.2	9.5
C(10)–C(11)–C(12)–C(13)	9.0	9.1	12.1	12.5
C(11)–C(12)–C(13)–C(14)	14.2	11.3	14.6	19.6
C(12)–C(13)–C(14)–C(15)	14.7	11.5	16.0	19.5
C(13)–C(14)–C(15)–O(3)	15.5	13.4	17.4	20.2

5. Conformation of the Epoxycyclohexane Ring. – The bond lengths and angles of the epoxycyclohexane ring in each of the independent molecules of **3** exhibit the normally expected values. The conformation of the epoxycyclohexane ring is that of a C(3)-sofa distorted towards a C(2),C(3)-half chair, with C(2) and C(3) on opposite sides of the plane through C(1), C(6), C(5), and C(4). The deviations from the mean ring plane for C(3) are 0.52, 0.60, 0.50, and 0.52 Å for the four independent molecules; the corresponding deviations of C(2) are 0.14, 0.11, 0.22, and 0.18 Å. Atom C(3) lies on the same side of the mean plane of the ring as the epoxy O-atom (*syn* to the epoxy O-atom), which brings the OH group at C(3) into the equatorial position. These observations are consistent with MM2 force-field calculations on molecules of (9′*Z*)-neoxanthin (**4**) [11], which indicated that the C(3)-sofa conformation is energetically preferred over the C(2)-sofa conformation, presumably because the C(2)-sofa has unfavourable intramolecular interactions between the Me substituents at C(1) and the epoxy O-atom. The calculations also showed that the *syn*-relationship between C(3) and the epoxy O-atom is preferred over the *anti*-conformation, which would place the OH group in an axial position. The relative populations of the *syn*- and *anti*-conformations were calculated to be 2:1.

The only other published structure of a violaxanthin derivative is 3,3,5-trimethyl-4-(3-oxobut-1-enyl)-4,5-epoxycyclohexyl 2,3,4,6-tetra-*O*-acetyl-*β*-D-glucopyranoside (**5**) [24]. This structure also exhibits the distorted C(3)-sofa *syn*-conformation with the C(3)–O group in the equatorial position. These conformations appear to be normal for epoxycyclohexanes, because distorted half-chair or sofa conformations have been reported for other simply substituted epoxycyclohexanes [12c].

6. Torsion Angles about the C(6)–C(7) Bond. – One purpose of the investigation of the structure of **3** was to determine the C(1)–C(6)–C(7)–C(8) torsion angle, ω_1 (*Fig. 4*), since the shapes of the CD spectra of this class of compounds are known to be sensitive to ω_1. For the four independent molecules of **3**, the torsion angles are –123.6(8)°, –116.9(8)°, –121.6(9)°, and –101.5(9)°, respectively. The variation in ω_1 for these independent molecules indicates the sensitivity of this torsion angle to crystal packing interactions. That the torsion angles about the C(6)–C(7) bond are sensitive to crystal packing has been suggested previously by *Bart* and *MacGillavry* [22] in a discussion of related carotenoid and retinal compounds.

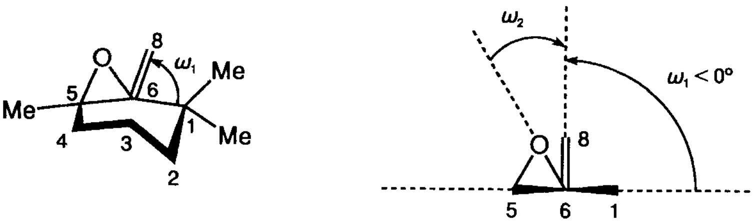

Fig. 4. *The location and definition of the torsion angles ω_1 and ω_2 in the violaxanthin end group*

Of interest is the orientation of the plane of the polyene chain with respect to the epoxide group. The corresponding torsion angle in **5** [24] is –109.5(6)°, in close agreement with the observed values for **3**. Is the magnitude of ω_1 determined only by steric and intermolecular interactions, or are other interactions also important?

It has been postulated [12b] that a π-system can interact with an epoxide ring by pseudoconjugation [12a]. In such cases, the plane of the atoms of the π-system should bisect the bond in the epoxide ring opposite the ring atom to which the π-system is attached. For violaxanthin derivatives, this postulation requires ω_1 to be *ca.* –166°, which is sterically unfavoured because of the interaction between the H-atom on C(8) and the Me group at C(5) [25]. A combination of pseudoconjugation and steric effects could lead to more accommodating values of ω_1; however, the deviation of ω_1 from the ideal value for pseudoconjugation lies between 43° and 66° for compounds **3** and **5** [24]. If pseudoconjugation effects were important, it is unlikely that such large deviations as those observed experimentally would be obtained.

A second possibility is that the lone-pair electrons of the epoxy O-atom, and not the entire epoxide ring, are interacting with the π-system of the side chain. In such a case the plane of the atoms of the π-system should lie parallel with the C(6)–O(2) bond. An examination of the O(2)–C(6)–C(7)–C(8) torsion angles, ω_2 (*Fig. 4*), for the violaxanthin derivatives reveals the values 10(1)°, 16(1)°, 11(1)°, and 32(1)° for **3** and 26.7(7)° for **5**

[24]. The positive sign for these angles also indicates that the plane of the conjugated side chain lies on the side of O(2) opposite to that of C(5), so that there is little likelihood that the plane of the π-system is attempting to bisect the C(5)–O(2) bond by the pseudoconjugation effect described above. The relatively small values for ω_2 show that the C(6)–O(2) bond is nearly eclipsed by the plane of the polyene chain, and the possibility of an interaction between the π-system of the conjugated chain and the lone-pair orbitals of the epoxy O-atom cannot be ruled out.

To see if there is a general tendency for π-systems substituted on epoxide rings to align themselves so that they eclipse the O-atom of the ring ($\omega_2 = 0°$), a search of the *Cambridge Structural Database* [26] was undertaken. The search question was designed to locate all organic structures in which an epoxide ring possessed at least one substituent connected to the ring by an acyclic C–C bond, and in which the substituent contained a π-system adjacent to this single bond. The π-system could consist of such groups as C=C, C=O, C=N, Ph, or conjugated systems. A further selection criterion was that atomic coordinates should be available. The search located 83 structures, of which 50 had $\omega_2 = 0 \pm 30°$ (41 had $\omega_2 = 0 \pm 20°$). A further 18 had the *anti*-alignment with $\omega_2 = 180 \pm 30°$. For Ph rings, the torsion angle closest to 0° was used, and the other torsion angle discarded. Some molecules had more than one substituent which fitted the criterion. In such cases, the torsion angle closest to 0° or 180° was taken, since steric interactions usually would not allow both substituents to be aligned with the O-atom. The remaining 15 structures, which had ω_2 well away from 0° or 180°, were often of very complex molecules in which steric interactions may have been an overriding factor, although this did not seem to be true in all cases.

The results of the above analysis are interesting in that 60% of all located structures had orientations which were quite close to that necessary for an interaction between the π-system and the lone-pair electrons of the epoxy O-atom ($\omega_2 = 0°$), and 82% have π-systems oriented near to either parallel or antiparallel with respect to the adjacent C–O bond of the epoxide ring. It remains unclear, however, whether or not such conformations for substituted epoxide rings are preferred merely on steric grounds.

7. Conclusions. – As indicated in the *Introduction*, we wished to determine if the differences between the CD spectra of zeaxanthin (**1**) and violaxanthin (**2**) could be correlated with either an electronic interaction between the epoxy O-atom and the π-system of the polyene chain, or with variations in the torsion angle, ω_1. Unfortunately, the only X-ray structure determination in the literature of a chiral compound which contains a zeaxanthin endgroup is that of *Ueda* and *Nowacki* [7], and errors in the published data for this structure make it difficult to make any clear deductions about ω_1. Therefore, this special problem remains unsolved.

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