Sesquiterpenoids. Part XV.[1] Conformation of Humulene: *X*-Ray Analysis of the Crystal Structure of Humulene Diepoxide †

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The crystal structure of the title compound has been elucidated by the symbolic addition procedure and the eleven-membered carbocyclic ring of the sesquiterpene shown to have the conformation previously reported for the humulene molecule in the humulene–silver nitrate adduct, the mean deviation between corresponding torsion angles in the two molecules being 8°. Crystallographic data for the diepoxide are $a = 15{\cdot}265(10)$, $b = 5{\cdot}794(3)$, $c = 16{\cdot}055(8)$ Å, $\beta = 103° 24(4)'$, $Z = 4$, space group $P2_1/c$. Diffractometer (Mo-K_α radiation) and photographic (Cu-K_α radiation) intensity data were merged to give 1127 $|F_o|$ values, and least-squares adjustment of the atomic co-ordinates and thermal parameters converged at R 7·5%.

THE sesquiterpene humulene[2] (1) has an eleven-membered triene ring which undergoes interesting transannular reactions, *e.g.* the tricyclic compounds α-caryophyllene alcohol (2) and humulene bromohydrin (3) are produced by treatment of the hydrocarbon with sulphuric acid[3] and *N*-bromosuccinimide,[4] respectively. Humulene forms a bis(silver nitrate) adduct,[5] and *X*-ray analyses of this adduct established the *trans*-stereochemistry of all three double bonds in the hydrocarbon.[6,7] The complexed hydrocarbon in the adduct has the conformation (4), and transannular cyclisations of this conformation rationalize the stereochemistries of products (2) and (3). Moreover, the stereochemistries of the sesquiterpenoids illudol[8] and marasmic acid[9] are consistent with the biogenesis of these natural products from a humulene-like precursor with a conformation of the type (4).[10] It is possible that (4) may represent the preferred conformation of humulene, but it must be borne in mind that formation of a complex with silver ions may favour a conformation which is relatively unimportant for the free hydrocarbon. Strain-energy calculations[11] are not yet available to throw light on the possible conformations of the undecatriene ring system, and as a preliminary to these we considered it desirable

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† No reprints available.

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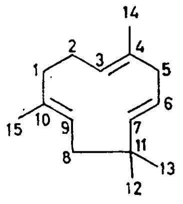
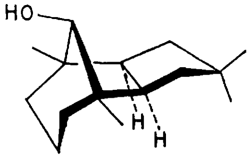
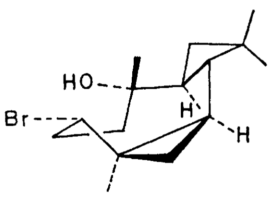
to obtain diffraction results for other humulene derivatives. Humulene itself is a liquid at room temperature and is conformationally mobile in that phase,[12] but humulene diepoxide (5) is a crystalline solid (m.p. 102—105 °C) [13] and we accordingly undertook an *X*-ray study of this compound.



(1)



(2)



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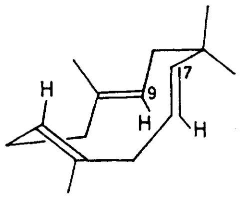

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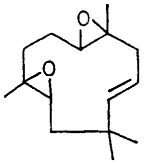

(5)

The crystal structure of the diepoxide was elucidated by the symbolic addition procedure for phase determination,[14] and the atomic parameters were subsequently adjusted by least-squares calculations which converged at *R* 7·5% over 1127 independent reflections. The resultant molecular structure is shown in Figure 1, and the arrangement of molecules in the crystal in Figure 2.

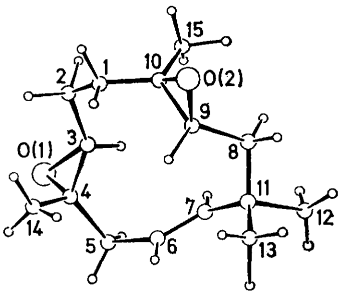

FIGURE 1 The molecular structure

The atomic co-ordinates and vibration parameters are listed in Tables 1 and 2, and the molecular dimensions in Table 3.

The conformation adopted by the carbon skeleton of the diepoxide approximates closely to (4). The torsion angles about the carbon–carbon bonds of the olefin (1) in its silver nitrate adduct and the diepoxide (5) are compared in Table 4 and the correspondence is very

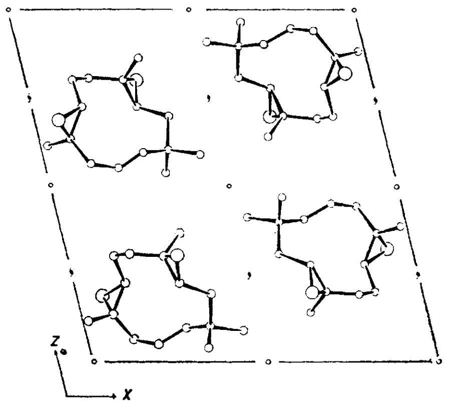

FIGURE 2 Arrangement of molecules in the unit cell

TABLE 1

Atomic co-ordinates (fractional × 10⁴ for carbon and oxygen, fractional × 10³ for hydrogen) with standard deviations in parentheses

	x	*y*	*z*
C(1)	8192(5)	−390(16)	1918(5)
C(2)	8661(5)	1976(15)	2003(5)
C(3)	8553(5)	3311(15)	2785(5)
C(4)	9091(4)	2920(15)	3656(5)
C(5)	8668(6)	3542(17)	4385(6)
C(6)	7943(4)	1843(15)	4468(4)
C(7)	7094(4)	2083(15)	4056(5)
C(8)	6144(5)	−648(15)	3050(5)
C(9)	6985(5)	−1315(14)	2750(4)
C(10)	7215(5)	−347(14)	1969(5)
C(11)	6350(4)	314(14)	3973(4)
C(12)	5485(5)	1516(22)	4098(6)
C(13)	6585(6)	−1633(18)	4636(6)
C(14)	9829(6)	1158(20)	3842(7)
C(15)	6606(6)	1238(18)	1377(6)
O(1)	9291(3)	4877(10)	3171(4)
O(2)	6854(3)	−2706(10)	1988(3)
H(1a)	834(5)	−117(15)	135(5)
H(1b)	847(4)	−164(12)	233(4)
H(2a)	830(4)	314(13)	146(4)
H(2b)	931(5)	151(13)	202(4)
H(3)	797(6)	414(16)	283(5)
H(5a)	845(4)	489(13)	434(4)
H(5b)	912(4)	359(12)	497(4)
H(6)	816(5)	34(15)	485(5)
H(7)	689(4)	350(13)	372(4)
H(8a)	572(4)	67(13)	263(4)
H(8b)	574(4)	−228(14)	302(4)
H(9)	751(4)	−188(13)	326(4)
H(12a)	497(6)	40(15)	393(5)
H(12b)	558(3)	223(10)	473(3)
H(12c)	530(4)	283(13)	373(4)
H(13a)	608(5)	−249(16)	460(5)
H(13b)	712(5)	−236(14)	456(5)
H(13c)	679(5)	−85(14)	518(5)
H(14a)	1000(5)	68(14)	332(5)
H(14b)	1034(6)	146(18)	434(6)
H(14c)	960(5)	−37(15)	402(5)
H(15a)	672(5)	82(16)	77(6)
H(15b)	589(6)	81(15)	128(5)
H(15c)	659(5)	271(16)	152(5)

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good, the mean deviation between equivalent angles being only 8°. Since epoxidation must necessarily have involved the outer faces of the C(3)=C(4) and C(9)=C(10) double bonds, (4) must represent the conformation of the humulene molecules immediately before and during the epoxidation reaction. A notable characteristic of the conformation of the eleven-membered ring is that the methyl groups C(14) and C(15) are on opposite faces of the mean molecular plane, whereas in a number of germacranolides with *trans*-ethylenic or epoxide functions

TABLE 2

(*a*) Anisotropic thermal parameters (× 10^4) † for the carbon and oxygen atoms

	b_{11}	b_{22}	b_{33}	b_{12}	b_{13}	b_{23}
C(1)	44(4)	311(36)	30(4)	53(21)	30(6)	42(21)
C(2)	37(4)	310(36)	35(4)	46(20)	21(6)	46(20)
C(3)	29(4)	258(32)	48(4)	−2(19)	21(6)	68(21)
C(4)	24(3)	337(35)	44(4)	−15(19)	23(6)	16(21)
C(5)	39(4)	238(35)	44(4)	−15(22)	18(7)	−96(22)
C(6)	27(3)	329(35)	23(3)	−9(19)	10(5)	−40(19)
C(7)	29(3)	243(32)	32(4)	12(18)	11(5)	−4(19)
C(8)	31(3)	292(32)	30(3)	−40(20)	9(6)	−46(18)
C(9)	36(4)	251(31)	26(3)	2(19)	14(6)	12(18)
C(10)	41(4)	264(32)	29(3)	35(20)	27(6)	−13(18)
C(11)	28(3)	228(30)	30(3)	2(17)	18(5)	14(17)
C(12)	30(4)	544(51)	42(5)	−4(25)	27(7)	−36(29)
C(13)	45(5)	332(39)	43(5)	−26(25)	25(8)	−9(24)
C(14)	41(5)	427(50)	49(5)	89(26)	14(9)	5(27)
C(15)	42(4)	284(41)	36(4)	57(22)	5(7)	23(22)
O(1)	45(3)	285(23)	61(3)	−73(14)	30(5)	10(15)
O(2)	53(3)	261(23)	36(3)	−17(14)	23(4)	−63(12)

(*b*) Isotropic thermal parameters (× 10) for the hydrogen atoms

	B		*B*		*B*
H(1a)	59(21)	H(7)	35(15)	H(13b)	45(18)
H(1b)	26(12)	H(8a)	38(15)	H(13c)	51(19)
H(2a)	37(14)	H(8b)	44(16)	H(14a)	43(17)
H(2b)	42(16)	H(9)	41(15)	H(14b)	76(27)
H(3)	71(24)	H(12a)	56(20)	H(14c)	40(18)
H(5a)	27(16)	H(12b)	16(10)	H(15a)	63(21)
H(5b)	31(13)	H(12c)	28(15)	H(15b)	58(19)
H(6)	53(20)	H(13a)	51(20)	H(15c)	49(22)

† The anisotropic temperature factors are expressed in the form: $T = \exp[-(b_{11}h^2 + b_{22}k^2 + b_{33}l^2 + b_{12}hk + b_{13}hl + b_{23}kl)]$.

TABLE 3

Molecular dimensions

(*a*) Bond lengths (Å)

C(1)–C(2)	1·538(13)	C(2)–H(2b)	1·01(9)
C(2)–C(3)	1·515(12)	C(3)–H(3)	1·02(11)
C(3)–C(4)	1·466(11)	C(5)–H(5a)	0·85(8)
C(3)–O(1)	1·468(11)	C(5)–H(5b)	1·02(7)
C(4)–C(5)	1·506(13)	C(6)–H(6)	1·07(8)
C(4)–C(14)	1·498(15)	C(7)–H(7)	0·99(7)
C(4)–O(1)	1·447(10)	C(8)–H(8a)	1·12(7)
C(5)–C(6)	1·510(13)	C(8)–H(8b)	1·13(8)
C(6)–C(7)	1·319(11)	C(9)–H(9)	1·06(8)
C(7)–C(11)	1·513(12)	C(12)–H(12a)	1·00(10)
C(8)–C(11)	1·546(10)	C(12)–H(12b)	1·07(6)
C(8)–C(9)	1·523(12)	C(12)–H(12c)	0·97(7)
C(9)–C(10)	1·488(11)	C(13)–H(13a)	0·91(10)
C(9)–O(2)	1·440(9)	C(13)–H(13b)	0·95(9)
C(10)–C(1)	1·514(13)	C(13)–H(13c)	0·97(8)
C(10)–C(15)	1·484(13)	C(14)–H(14a)	0·98(8)
C(10)–O(2)	1·476(10)	C(14)–H(14b)	1·00(11)
C(11)–C(12)	1·546(14)	C(14)–H(14c)	1·02(8)
C(11)–C(13)	1·535(12)	C(15)–H(15a)	1·05(9)
C(1)–H(1a)	1·08(9)	C(15)–H(15b)	1·09(10)
C(1)–H(1b)	1·00(7)	C(15)–H(15c)	0·89(9)
C(2)–H(2a)	1·14(7)		

TABLE 3 (*Continued*)

(*b*) Valency angles (deg.)

C(2)–C(1)–C(10)	115·2(7)	C(4)–C(3)–H(3)	108(4)
C(1)–C(2)–C(3)	113·0(5)	O(1)–C(3)–H(3)	106(4)
C(2)–C(3)–C(4)	124·6(6)	C(4)–C(5)–H(5a)	113(4)
C(2)–C(3)–O(1)	116·5(6)	C(4)–C(5)–H(5b)	114(3)
C(4)–C(3)–O(1)	59·1(5)	C(6)–C(5)–H(5a)	109(4)
C(3)–C(4)–C(5)	117·3(6)	C(6)–C(5)–H(5b)	107(3)
C(3)–C(4)–C(14)	121·7(6)	H(5a)–C(5)–H(5b)	103(6)
C(3)–C(4)–O(1)	60·5(5)	C(5)–C(6)–H(6)	117(4)
C(5)–C(4)–C(14)	116·4(6)	C(7)–C(6)–H(6)	120(4)
C(5)–C(4)–O(1)	114·4(6)	C(6)–C(7)–H(7)	120(4)
C(14)–C(4)–O(1)	113·5(6)	C(11)–C(7)–H(7)	112(4)
C(4)–C(5)–C(6)	111·5(6)	C(9)–C(8)–H(8a)	113(3)
C(5)–C(6)–C(7)	122·9(5)	C(9)–C(8)–H(8b)	106(3)
C(6)–C(7)–C(11)	127·1(6)	C(11)–C(8)–H(8a)	107(3)
C(9)–C(8)–C(11)	113·3(6)	C(11)–C(8)–H(8b)	109(3)
C(8)–C(9)–C(10)	123·5(5)	H(8a)–C(8)–H(8b)	108(6)
C(8)–C(9)–O(2)	116·7(4)	C(8)–C(9)–H(9)	112(3)
C(10)–C(9)–O(2)	60·5(5)	C(10)–C(9)–H(9)	119(4)
C(1)–C(10)–C(9)	117·8(6)	O(2)–C(9)–H(9)	115(3)
C(1)–C(10)–C(15)	117·0(5)	C(11)–C(12)–H(12a)	108(4)
C(1)–C(10)–O(2)	111·3(6)	C(11)–C(12)–H(12b)	111(2)
C(15)–C(10)–C(9)	122·6(6)	C(11)–C(12)–H(12c)	115(3)
C(15)–C(10)–O(2)	113·9(6)	H(12a)–C(12)–H(12b)	115(6)
C(9)–C(10)–O(2)	58·1(5)	H(12a)–C(12)–H(12c)	104(6)
C(7)–C(11)–C(8)	108·1(5)	H(12b)–C(12)–H(12c)	103(5)
C(7)–C(11)–C(12)	109·2(6)	C(11)–C(13)–H(13a)	108(4)
C(7)–C(11)–C(13)	112·7(5)	C(11)–C(13)–H(13b)	108(4)
C(8)–C(11)–C(12)	107·3(6)	C(11)–C(13)–H(13c)	105(3)
C(8)–C(11)–C(13)	111·3(6)	H(13a)–C(13)–H(13b)	119(8)
C(12)–C(11)–C(13)	108·1(7)	H(13a)–C(13)–H(13c)	114(7)
C(3)–O(1)–C(4)	60·4(5)	H(13b)–C(13)–H(13c)	102(7)
C(9)–O(2)–C(10)	61·3(5)	C(4)–C(14)–H(14a)	111(3)
C(2)–C(1)–H(1a)	105(3)	C(4)–C(14)–H(14b)	117(5)
C(2)–C(1)–H(1b)	118(3)	C(4)–C(14)–H(14c)	111(4)
C(10)–C(1)–H(1a)	117(4)	H(14a)–C(14)–H(14b)	115(8)
C(10)–C(1)–H(1b)	105(3)	H(14a)–C(14)–H(14c)	100(7)
H(1a)–C(1)–H(1b)	96(6)	H(14b)–C(14)–H(14c)	100(8)
C(1)–C(2)–H(2a)	109(3)	C(10)–C(15)–H(15a)	104(4)
C(1)–C(2)–H(2b)	101(3)	C(10)–C(15)–H(15b)	114(4)
C(3)–C(2)–H(2a)	102(3)	C(10)–C(15)–H(15c)	118(5)
C(3)–C(2)–H(2b)	114(3)	H(15a)–C(15)–H(15b)	101(8)
H(2a)–C(2)–H(2b)	118(6)	H(15a)–C(15)–H(15c)	119(7)
C(2)–C(3)–H(3)	124(4)	H(15b)–C(15)–H(15c)	100(7)

TABLE 4

Torsion angles (deg.) for the carbon skeletons of humulene diepoxide and the humulene–silver nitrate adduct

	Diepoxide	Silver adduct
C(10)–C(1)–C(2)–C(3)	52	35
C(1)–C(2)–C(3)–C(4)	80	77
C(2)–C(3)–C(4)–C(5)	−153	−162
C(2)–C(3)–C(4)–C(14)	2	12
C(3)–C(4)–C(5)–C(6)	73	95
C(14)–C(4)–C(5)–C(6)	−84	−80
C(4)–C(5)–C(6)–C(7)	−89	−94
C(5)–C(6)–C(7)–C(11)	169	156
C(6)–C(7)–C(11)–C(8)	−106	−102
C(6)–C(7)–C(11)–C(12)	137	142
C(6)–C(7)–C(11)–C(13)	17	18
C(7)–C(11)–C(8)–C(9)	47	55
C(12)–C(11)–C(8)–C(9)	165	173
C(13)–C(11)–C(8)–C(9)	−77	−70
C(11)–C(8)–C(9)–C(10)	−123	−126
C(8)–C(9)–C(10)–C(11)	157	172
C(8)–C(9)–C(10)–C(15)	−4	−5
C(9)–C(10)–C(1)–C(2)	−109	−109
C(15)–C(10)–C(1)–C(2)	54	69

TABLE 5

Torsion angles (deg.) in the epoxide groups

O(1)–C(4)–C(3)–C(2)	103	O(2)–C(10)–C(9)–C(8)	−104
O(1)–C(3)–C(4)–C(5)	104	O(2)–C(9)–C(10)–C(1)	−99
O(1)–C(3)–C(4)–C(14)	−101	O(2)–C(9)–C(10)–C(15)	100
C(4)–O(1)–C(3)–C(2)	−116	C(10)–O(2)–C(9)–C(8)	115
C(3)–O(1)–C(4)–C(5)	−109	C(9)–O(2)–C(10)–C(1)	110
C(3)–O(1)–C(4)–C(14)	114	C(9)–O(2)–C(10)–C(15)	−115

C(14) and C(15) are on the same face of the ten-membered rings.[15]

The epoxide groupings are characterized by *trans*-C–C–C–C torsion angles of 153 and 157, mean 155°; the C–C–O–C torsion angles are in the range 109—116, mean 113°, and the C–C–C–O angles are 99—104, mean 102°. Similar results have been obtained for germacranolide epoxides.[15] The C–C bond of the epoxides, the C(epoxide)–C(sp^3) bonds, and the C(epoxide)–O bonds have mean lengths of 1·477, 1·507, and 1·458 Å, respectively, indicating that the radius of C(epoxide) is *ca.* 0·74 Å, not distinguishable from that appropriate to C(sp^2). The mean C(sp^3)–C(sp^3) and C(sp^3)–C(sp^2) bond lengths are 1·541 and 1·512 Å, respectively. The C(sp^3)–C(epoxide)–C(epoxide) valency angles are slightly larger than the C(sp^3)–C(epoxide)–O valency angles, the former being in the range 117·3—124·6, mean 121·3°, whereas the latter are 111·3—116·7, mean 114·4°. The C(sp^3)–C(epoxide)–C(sp^3) angles are 116·4 and 117·0, mean 116·7°.

EXPERIMENTAL

Crystal Data.—$C_{15}H_{24}O_2$, M = 236·4. Monoclinic, a = 15·265(10), b = 5·794(3), c = 16·055(8) Å, β = 103° 24(4)′, U = 1381 Å^3, D_m = 1·10, Z = 4, D_c = 1·13, $F(000)$ = 520. Space group $P2_1/c$ (C^5_{2h}). Mo-K_α radiation, λ = 0·7107 Å, μ(Mo-K_α) = 0·71 cm^{-1}; Cu-K_α radiation, λ = 1·5418 Å, μ(Cu-K_α) = 5·05 cm^{-1}.

Crystallographic Measurements.—Cell dimensions and intensities were measured with zirconium-filtered Mo-K_α radiation on a Hilger and Watts computer-controlled four-circle diffractometer. Because of the very small size of the crystal many of the reflections had $I < 3\sigma(I)$, and the data set was therefore extended in the high sin θ range by obtaining long-exposure Cu-K_α Weissenberg photographs of the h0—3l layers, which were then measured on a flying-spot densitometer. The diffractometer data and *ca.* 700 photographic data were merged to yield intensities for 1127 independent reflections.

Structure Analysis.—Phases were determined by the symbolic addition procedure. Three reflections were given signs to define the origin and four given symbols as shown in Table 6.* After more signs were generated in terms of the symbols it became clear that $a = c$ = negative and $b = d$ = positive, and 84 reflections with $E > 1{\cdot}5$ were phased. Reflections in the range $1{\cdot}3 < E < 1{\cdot}5$ were then considered, and sign relationships extended to give a total of 127 fully consistent phases. An E map calculated with these phases had exactly 17 large peaks, which proved to correspond to the 15 carbon and 2 oxygen atoms.

The initial co-ordinates gave R 40·6%, and after three rounds of full-matrix least-squares refinement with isotropic temperature factors R was 14·2%. All 24 hydrogen atoms were located in a difference electron-density distribution, and subsequent refinement with anisotropic temperature factors for the carbon and oxygen atoms and isotropic temperature factors for the hydrogen atoms converged at R 7·5%. Unit weights were used in all these calculations, and were shown to be satisfactory by analysis of $w\Delta^2$ as a function of $|F_o|$.

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* Table 6 together with the final observed and calculated structure factors is listed in Supplementary Publication No. SUP 20625 (25 pp., 1 microfiche). For details see Notice to Authors No. 7 in *J. Chem. Soc.* (*A*), 1970, Issue No. 20.

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