The Structure and Conformation of Umbellifolide, a 4,5-Secoeudesmane Derivative

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Umbellifolide (3) is the first 4,5-secoeudesmane derivative discovered in nature. Its structure and conformation have been determined by physical methods, including X-ray analysis. Umbellifolide, both in solution and in the solid state, exists as a $\theta = 60°$ boat cyclohexanone rotamer. The *exo*-methylene γ-lactone group, *cis*-closed at C(8), is almost planar and belongs to the pseudo-rotational P-type. The X-ray determination was based on 1 047 diffractometer intensities and the least-squares refinement converged to $R = 0.046$. A possible biogenesis of umbellifolide from a $\Delta^{4,5}$-eudesmane precursor (5) *via* fragmentation of 4-hydroxy-5-hydroperoxyeudesmane intermediates is proposed.

As a part of an investigation of alpine plants,[1-3] *Artemisia umbelliformis* Lam., a rare species of commercial importance for its use in the production of liqueurs,[4] has been examined. In previous work [5] the isolation and the structural elucidation of the hydroperoxyeudesmanolides, 5-desoxy-5-hydroperoxy-telekin (1) and 5-desoxy-5-hydroperoxy-5-*epi*-telekin (2), from chloroform extracts of this plant were described. From the more polar fractions of the same extracts a crystalline, extremely bitter, diketo-γ-lactone has now been isolated. This compound was named umbellifolide and has been shown to possess the hitherto unreported 4,5-secoeudesmane skeleton (3). The present paper reports the study of its structure and conformation, both in solution and in the solid state.

Results and Discussion

Owing to the rarity of *A. umbelliformis* Lam. and to the relatively low yields of umbellifolide isolated (0.015%), only limited amounts were available: the structural elucidation of this compound therefore relied solely on physical methods.

Umbellifolide (3), $C_{15}H_{20}O_4$ (high resolution mass spectrum), is a diketo-γ-lactone, as shown by its [13]C n.m.r. spectrum, which displayed three carbonyl absorptions, two of which (δ 207.8 and 212.2 p.p.m.) appeared at the very low fields characteristic of unconjugated ketones. The presence of two deshielded doublets (δ 6.30 and 5.64) in the [1]H n.m.r. spectrum, and of absorption bands at 1 750 and 1 650 cm⁻¹ in the i.r. spectrum, indicated that (3) was an *exo*-methylene-γ-lactone: since no other centres of unsaturation were present ([13]C n.m.r. spectrum), (3) is monocyclic. The multiplicity of signals in the [13]C n.m.r. spectrum fitted none of the commonly encountered sesquiterpene lactone skeletons: double-resonance experiments allowed the assessment of the presence of partial formulae (A) and (B) (numbering as in the final formula; symbol ■ indicates a carbon atom not bonded to any hydrogen atom). Furthermore the [1]H n.m.r. spectrum revealed the presence of two methyl groups (δ 1.04 and 2.09), which, according to their chemical shift, were assigned to an angular methyl and to a methyl adjacent to a keto group respectively.

Formula (3) alone fitted these results whilst also being in accord with the downfield position of the C(6) protons

(1)

(2)

(3)

(A)

(B)
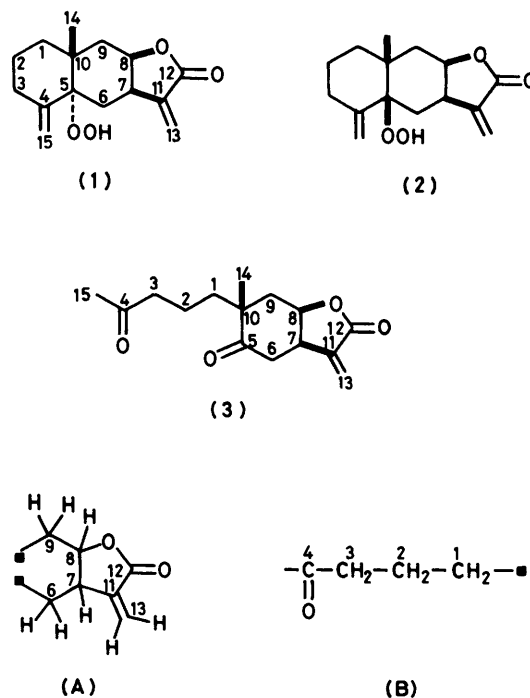
compared with those at C(9) (Table 1). This formula is also in good accord with the mass spectrum, which displayed a strong fragmentation peak at m/z 180, formed from the parent ion through a McLafferty rearrangement (Scheme 1).

In spite of the simplicity of its formula, the stereochemistry of umbellifolide proved rather difficult to establish: the [1]H n.m.r. pattern of 7-H (α on biogenetic grounds [6]) and of 8-H showed a *trans*-diaxial interaction with one of the adjacent methylene protons (Table 1), thus establishing the axial orientation of these methines. $J_{7,8}$ was high (9 Hz) showing either an antiperiplanar or synperiplanar relationship between these protons. Furthermore, the values of $J_{7,13}$ (2.8 and 2.5 Hz) are consonant both with a *cis*-lactone of the pseudorotational P-type [7] and a *trans*-lactone of an extreme

Table 1. ^{1}H and ^{13}C N.m.r. data. Spectra were determined at 200 and 50.3 MHz respectively, with SiMe$_4$ as internal standard; chemical shifts (δ) are expressed in p.p.m.; H–H coupling constants are expressed in Hz and given in parentheses; starred assignments in the ^{13}C n.m.r. spectrum have been confirmed by selective proton decouplings. The other assignments are based upon multiplicities and chemical shift considerations

^{1}H N.m.r. (CDCl$_3$)			^{13}C N.m.r. (CDCl$_3$)	
1a,b-H 2a,b-H	1.45 †		C(1)	17.65t
			C(2)	36.56t
3a,b-H	2.42brt	(6.5; 6.0)	C(3)	43.06t *
6α-H	2.70dd	(15.5; 7.0)	C(4)	207.8s
6β-H	2.54dd	(15.5; 8.5)	C(5)	212.2s
7-H	3.52m	(9.0; 8.5; 7.0; 2.8; 2.5)	C(6)	40.73t *
8-H	4.97td	(9.0; 9.0; 6.0)	C(7)	37.16d *
9α-H	2.33dd	(14.5; 6.0)	C(8)	79.95d *
9β-H	1.86dd	(14.5; 9.0)	C(9)	37.93t *
13a-H	6.30d	(2.8)	C(10)	45.68s
13b-H	5.64d	(2.5)	C(11)	138.01s
14-H	1.04s		C(12)	164.15s
15-H	2.09s		C(13)	123.45t *
			C(14)	22.78q *
			C(15)	29.93q *

† Centrum of the ABCD X$_2$ system.

Scheme 1.

m/z 264 (8%) → m/z 180 (100%) +

pseudo-rotational S-type.* Therefore the alternatives of a cis-lactone in a boat conformation (C) and that of a trans-lactone in a chair conformation (D) were not distinguishable. Although *A. umbelliformis* was found to contain both cis-

(4)

* In C(8) trans-lactones the allylic angle φ (H$_B$,C$_D$) [∠H(7)C(7)-C(11)C(13) [7]] may seemingly assume values above 90° or close to 60° and therefore values of the allylic constants $J_{7,13}$ less than usual can be found; [7,8] the C(8) trans-germacranolide chrysanolide has for instance $J_{7,13}$ 2.9 and 2.4 Hz [9] and values smaller than 3 Hz are commonly encountered in C(8) trans-eudesmanolides. [7,8] Just as the Karplus equation cannot easily distinguish values of dihedral angles near 0° and 180°, in the same way the generalized lactone rule [7] cannot distinguish between values of the allylic angle φ (H$_B$,C$_D$) approaching 60° (P-type) and 120° (extreme pseudo-rotational S-type).
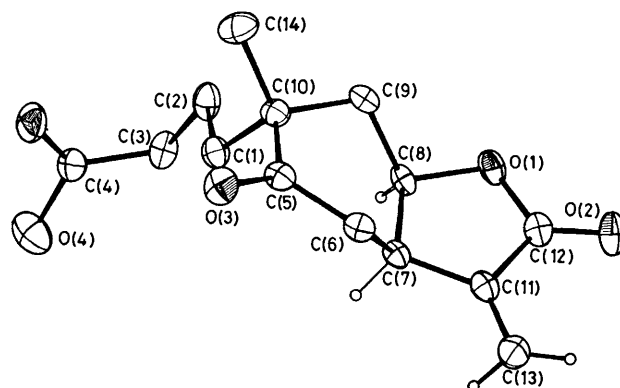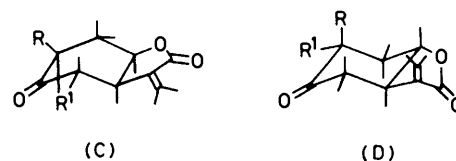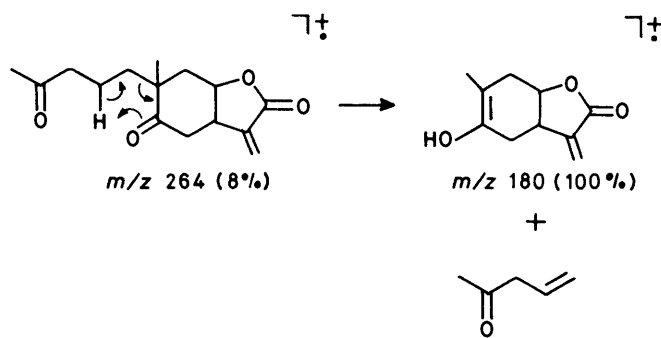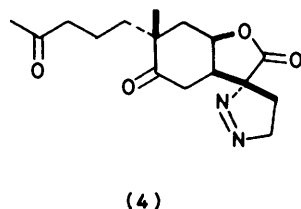

Figure 1. ORTEP II drawing of one molecule of umbellifolide at the 20% probability level. The H atoms at C(7) and C(8) have been included to show the cis-junction and those at C(13) to evidence the methylene group

and trans-lactones, [5] in the case of umbellifolide the alternative of a cis-lactone seemed biogenetically more plausible since all the other C(8) lactones isolated from this plant were of the cis-type. [5]

The c.d. curve of (3) displayed no maximum in the zone of the n $\longrightarrow$ π^* transition of the conjugated lactone carbonyl group. However, treatment of (3) with diazomethane gave a crystalline pyrazoline derivative (4), the long wavelength c.d. azochromophore band of which was strongly positive (Θ_{320} = +26 900°), suggesting a C-8 cis-lactone structure [10] since the attack of CH$_2$N$_2$ must come from the less hindered α side of (3). The α approach of CH$_2$N$_2$ was further confirmed by the downfield position of 8-H in (4) (δ 5.56). The unusual chemical shift of C-1 (17.65 p.p.m.) was explicable on the basis of the presence of a strong syn-diaxial interaction between this methylene and the protons at C-7 and C-8, thus requiring an α-axial orientation of the 4-oxobutyl chain. Structure (3) and conformation (C; R = CH$_3$, R^1 = C$_5$H$_9$O) were therefore likely for umbellifolide.

The X-ray diffraction analysis confirmed that umbellifolide is a cis-lactone and showed that the boat conformation found in solution is also adopted in the solid state. Figure 1 displays the ORTEP II drawing [11] of one molecule whilst Figure 2 displays the unit-cell content. The lactone ring is rather flat: O(1) is only at 0.107(3) Å from the mean plane through the other four atoms of the ring [root mean square difference = 0.021(3) Å]. Therefore the envelope conformation is only slightly pronounced. The bond distances and angles within the ring (Table 3) are comparable to those of other methylene lactones. [12] The C=O and C=CH$_2$ bonds deviate very slightly from planarity, the C(13)–C(11)–C(12)–O(2) torsion angle being 2.6(3)°. Other relevant torsion angles of the lactone ring are given in Table 4. The $\Sigma|\omega|$ over the endocyclic torsion angles of this ring is only 23.7°. A Newman projection down C(7)–C(11) confirms that the lactone ring is of the P-type [7] [∠H(7)C(7)C(11)C(13) = +59(2)°, given the absolute configuration of Figure 1; see also below]. The boat form of the
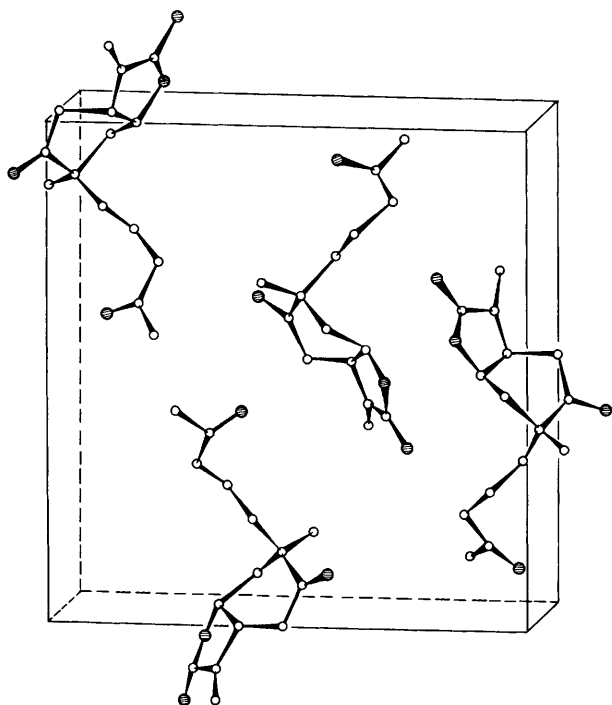
Figure 2. ORTEP II drawing of the content of the unit cell of umbellifolide

Scheme 2.

cyclohexanone ring is highly symmetric since the opposite bonds (Table 3, Figure 1) are equal including the diplanar pair C(5)–C(10) and C(7)–C(8) which are of different nature: the sp²–sp³ C(5)–C(10) bond [1.542(5) Å] is, in fact, unexpectedly strained. The mean plane through C(5), C(7), C(8), C(10) has a root mean square difference = 0.079(4) Å with C(6) at 0.533(3) Å and C(9) at 0.653(3) Å. The C_{sp^3}–C_{sp^3} bond lengths of the molecule are normal [$\langle C_{sp^3}$–$C_{sp^3}\rangle$ = 1.528(3)Å] as are the C_{sp^2}–C_{sp^3} lengths [$\langle C_{sp^2}$–$C_{sp^3}\rangle$ = 1.497(2) Å on excepting C(5)–C(10)]; C(14) is on the β-face and equatorial. The boat conformation of umbellifolide can be described, according to the notation of Hazebrook and Oosterhoff [13] as a θ = 60° cyclohexanone boat form. The energy of the boat forms of cyclohexanone is considerably lower than that of the boat rotamer of cyclohexane.[14] Furthermore in the case of umbellifolide, the boat conformation seems to be stabilized over the chair form by its cis-junction with the exo-methylene-γ-lactone group. The value of ω_3 calculated for the minimum energy conformation [15] of an isolated α-methylene-γ-lactone is 20°: models show that where there is a junction between this group and an undistorted six-membered ring in the boat conformation, this angle should be 0°, a value closer to 20° than the 60° which is required by the junction to a ring in the chair conformation [compare (C) with (E) and (F)]. The experimental value of this angle is −7.8(3)° in the present structure. Two chair conformations would be possible for umbellifolide: (E) associated with a lactone of the A-type and (F) associated with a lactone of the S-type. Structure (F) seems a priori more stable than (E), considering the presence in the latter conformation of a 1,3-diaxial interaction between the C-10 methyl group and the ether lactone oxygen. Since the chair form (F) is apparently unstrained, and taking into account the 3-alkyl-ketone effect,[16] the existence of umbellifolide in a boat conformation can be ascribed to conformational preferences by the lactone ring. A planar lactone (P-type) seems, therefore, to be more stable than a puckered
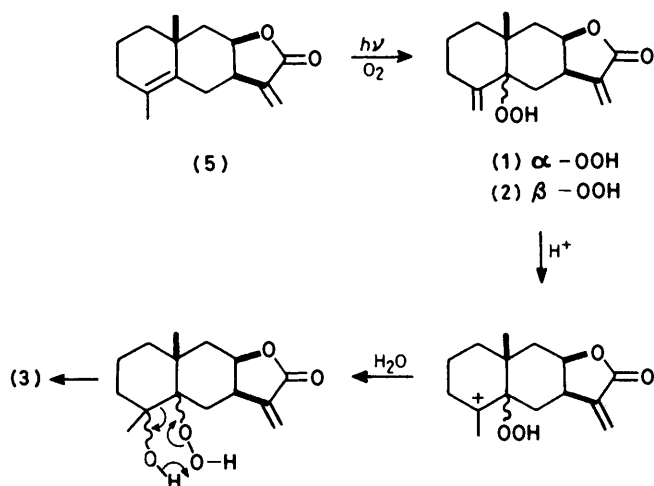
one (A,S-type) by an order of magnitude of at least 2.8 ± 1 kcal mol⁻¹, the conformational energy of the θ = 60° boat conformation of cyclohexanone.[14]

(E)   (F)
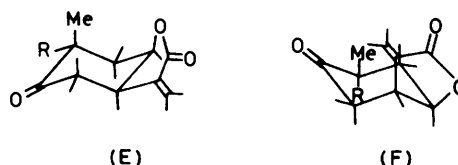
Given the absolute configuration displayed in Figure 1 (vide infra), the sign of the small torsion angle C(13)–C(11)–C(12)–O(2) [ω_2 = 2.6(3)°, lactone chromophore torsion angle] is positive. This sign is not paired with that of the C(11)–C(7)–C(8)–O(1) angle [ω_3 = −7.8(4), ring junction torsion angle], a result in contrast to the general relationship between the signs of these angles found both in cis- and trans-lactones.[12,17] To our knowledge, in the case of cis-lactones this anomalous result had been previously found in four cases only: the guaianolide florilenalin,[18] the helenanolide hymenograndin,[19] the ambrosanolide rudmollin,[20] and the xanthanolide parthemollin.[21] All these compounds, like umbellifolide, have an almost flat γ-lactone ring in the solid state.

The c.d. curve of umbellifolide lacked any apparent maximum in the range 245—260 nm, where the n ⟶ π* transition of the conjugated lactone carbonyl is expected. An extremum at 280 nm was attributed to the cyclohexanone chromophore: on the basis of the negative sign of this band (Θ_{280} = −1 600°), it is likely that structure (3) also represents the absolute configuration of umbellifolide; application of the octant rule to the boat cyclohexanone system of umbellifolide, as depicted in Figure 1, predicts, in fact, a negative extremum since both the 4-oxobutyl side-chain and the lactone ring lie in negative octants.

Umbellifolide (3) can be formally considered as the product of ozonolysis of the bridgeheaded double-bond of compound (5). On the basis of the co-occurrence of (3) and the hydroperoxides (1) and (2), derivable from the photooxygenation of (5), the mechanism illustrated in Scheme 2 may be proposed for the conversion of (5) into umbellifolide: photo-oxygenation of (5) would give the hydroperoxides (1) and (2) which, on protonation of the exocyclic C(4)=C(15)

Table 2. Atomic co-ordinates ($\times 10^4$) and temperature factors ($\text{Å}^2 \times 10^3$)

Atom	x	y	z	U
C(1)	4 134(7)	9 253(2)	2 130(2)	51(1) *
C(2)	2 611(9)	8 652(3)	2 658(2)	65(2) *
C(3)	3 953(8)	8 034(2)	3 207(2)	64(2) *
C(4)	5 153(7)	8 447(2)	3 941(2)	59(1) *
C(5)	4 730(7)	10 278(2)	947(2)	48(1) *
C(6)	5 350(7)	9 942(2)	93(2)	49(1) *
C(7)	5 411(6)	8 944(2)	49(2)	39(1) *
C(8)	3 242(7)	8 530(2)	409(2)	43(1) *
C(9)	1 638(7)	9 166(2)	811(2)	46(1) *
C(10)	2 886(7)	9 771(2)	1 435(2)	48(1) *
C(11)	5 493(7)	8 599(2)	−835(2)	47(1) *
C(12)	3 394(7)	8 084(2)	−983(2)	54(1) *
C(13)	7 061(8)	8 730(2)	−1 419(2)	63(1) *
C(14)	1 221(8)	10 435(3)	1 820(3)	75(2) *
C(15)	7 017(9)	7 936(3)	4 344(3)	93(2) *
O(1)	2 087(5)	8 098(2)	−291(2)	57(1) *
O(2)	2 818(6)	7 697(2)	−1 604(2)	80(1) *
O(3)	5 653(5)	10 913(1)	1 252(2)	73(1) *
O(4)	4 608(6)	9 145(2)	4 212(2)	85(1) *

* Equivalent isotropic U defined as one third of the trace of the orthogonalized U_{ij} tensor.

bond, and stabilization of the resulting cation by a water molecule,* could give compounds of the β-hydroxy hydroperoxy type; dehydration of the latter products through a six-membered concerted mechanism, should lead to umbellifolide. Hydroperoxides have also been postulated as intermediates in the biogenesis of 1,10-seco-eudesmanolides.[22]

Experimental

M.p.s were determined on a Büchi SMP-20 apparatus and are uncorrected. Optical rotations were measured on a Perkin-Elmer 141 automatic polarimeter in $CHCl_3$ solution; c.d. spectra were taken on a Jobin Yvon Mark III apparatus in methanolic solution. High- and low-resolution mass spectra were obtained on a Cratos MS 80 and a Varian Mat CH7 A apparatus respectively. U.v. spectra were taken in 95% EtOH solution on a Beckman DB-GT spectrophotometer. I.r. spectra were recorded on a Perkin-Elmer model 237 spectrophotometer. ^1H N.m.r. spectra were obtained on a Varian XL 200 spectrometer. ^{13}C N.m.r. spectra were taken on a Varian XL 100 spectrometer. Silica gel 60 (70—230 mesh, Merck) was used for the column chromatography separations. Analytical and preparative (thickness: 2 mm) t.l.c. was carried out on silica gel G F254 pre-coated plates (Merck). Spots were revealed by spraying with H_2SO_4 and heating at 100 °C.

Plant Material.—*Artemisia umbelliformis* Lam. came from experimental cultivations at the Giardino Botanico Alpino ' Paradisia ' (Cogne, Aoste, Italy) and from the Centro Sperimentale Coltura Fiori, Erbe Alpine ' Regina delle Alpi ' (Pietraporzio, Cuneo, Italy).

Isolation of Umbellifolide.—The aerial parts of the dried flowers (1 kg) were ground and then extracted with $CHCl_3$ at room temperature. Further purification of the extract, as described in ref. 5, gave a thick syrup (35 g) which was chro-

Table 3. Bond lengths (Å) and angles (°); e.s.d.s in parentheses

C(1)–C(2)	1.535(6)	C(1)–C(10)	1.547(5)
C(2)–C(3)	1.511(6)	C(3)–C(4)	1.505(5)
C(4)–C(15)	1.491(6)	C(4)–O(4)	1.197(4)
C(5)–C(6)	1.499(5)	C(5)–C(10)	1.542(5)
C(5)–O(3)	1.214(4)	C(6)–C(7)	1.532(4)
C(7)–C(8)	1.533(5)	C(7)–C(11)	1.506(4)
C(8)–C(9)	1.499(5)	C(8)–O(1)	1.463(4)
C(9)–C(10)	1.544(5)	C(10)–C(14)	1.537(6)
C(11)–C(12)	1.482(5)	C(11)–C(13)	1.323(6)
C(12)–O(1)	1.344(5)	C(12)–O(2)	1.201(4)
C(2)–C(1)–C(10)	115.2(4)	C(1)–C(2)–C(3)	113.0(4)
C(2)–C(3)–C(4)	115.4(3)	C(3)–C(4)–C(15)	117.1(3)
C(3)–C(4)–O(4)	122.1(4)	C(15)–C(4)–O(4)	120.7(4)
C(6)–C(5)–C(10)	117.0(3)	C(6)–C(5)–O(3)	122.0(3)
C(10)–C(5)–O(3)	121.0(3)	C(5)–C(6)–C(7)	112.9(3)
C(6)–C(7)–C(8)	112.1(3)	C(6)–C(7)–C(11)	113.2(3)
C(8)–C(7)–C(11)	103.3(3)	C(7)–C(8)–C(9)	114.3(3)
C(7)–C(8)–O(1)	106.7(3)	C(9)–C(8)–O(1)	109.3(3)
C(8)–C(9)–C(10)	111.6(3)	C(1)–C(10)–C(5)	106.7(3)
C(1)–C(10)–C(9)	112.1(3)	C(5)–C(10)–C(9)	108.1(3)
C(1)–C(10)–C(14)	110.8(3)	C(5)–C(10)–C(14)	108.3(3)
C(9)–C(10)–C(14)	110.7(3)	C(7)–C(11)–C(12)	108.1(3)
C(7)–C(11)–C(13)	128.8(3)	C(12)–C(11)–C(13)	123.1(3)
C(11)–C(12)–O(1)	109.5(3)	C(11)–C(12)–O(2)	128.9(4)
O(1)–C(12)–O(2)	121.6(4)	C(8)–O(1)–C(12)	111.7(3)

matographed on a silica gel (400 g) column with $CHCl_3$ as eluant; 200-ml fractions were collected. Fractions 22—23 gave umbellifolide (150 mg, 0.015% based on dried plants).

Umbellifolide (3) [(3aR,6R,7R)-2,4-*Dioxo-6-methyl-3-methylene*-2,3,3a,4,5,6,7,7a-*octahydro*-6-(4-*oxobutyl*)*benzofuran*].—The compound crystallized from ethyl acetate–ether as needles m.p. 113 °C, $[\alpha]_D^{25} = +60.8°$ (c, 0.5); $\nu_{max.}$ (KBr) (no OH), 1 760 (γ-lactone), 1 705 (C=O) and 1 660 (C=C); $\lambda_{max.}$ 220 (log ε 4.3); m/z (rel. int.) 264.136 90 (M^+) ($C_{15}H_{20}O_4$ requires 264.136 15, 6%), 180 ($C_{10}H_{12}O_3$, 100%), 84 (C_5H_8O, 30%), and 43 (15%); c.d. $\Theta_{280} = +1\ 600°$, $\Theta_{220} = -8\ 400°$.

Pyrazoline Adduct of Umbellifolide (4).—A sample of umbellifolide (51 mg) in $CHCl_3$ (1 ml) was treated overnight with ether (20 ml) containing CH_2N_2 (ca. 0.8 g) (generated from *N*-methyl-*N'*-nitro-*N*-nitrosoguanidine). Removal of the solvent left a silky mass of crystals (56 mg) which after being washed with ether had m.p. 162—164 °C (decomp.), $[\alpha]_D^{25} = +250°$ (c, 0.5); $\nu_{max.}$ (KBr) 1 785 (γ-lactone), 1 705 (C=O), no olefinic double-bond band, 1 555 (diazene group); c.d. $\Theta_{320} = +26\ 900°$ and $\Theta_{237} = +11\ 800°$.

Crystal Data.—Umbellifolide is orthorhombic, space group $P2_12_12_1$, $a = 5.865(2)$, $b = 15.326(6)$, $c = 15.930(9)$ Å, $V_c = 1\ 432(1)$ Å^3, $Z = 4$, $D_c = 1.23$ g cm^{-3}, graphite monochromatized Mo-K_α radiation, $\lambda = 0.710\ 69$ Å, μ(Mo-K_α) = 0.09 mm^{-1}.

Data Collection.—A crystal of dimensions $0.25 \times 0.20 \times 0.27$ mm^3 was mounted on a Nicolet R3 diffractometer. The cell parameters were obtained and refined from 16 reflexions, $25° < 2\theta < 35°$. The intensities were measured with the ω-scan technique at variable speed: from $1.5°$ min^{-1} for the weakest to $15.0°$ min^{-1} for the strongest reflexions. Periodic remeasurements of one standard reflexion indicated no decay in the X-ray beam. One octant of the reciprocal lattice sphere was explored up to $2\theta = 50°$; a total of 1 356 reflexions were measured and 1 055, with $I \geqslant 2\sigma(I)$ were considered as

* Other alternatives for the stabilization of this cation are of course possible, *e.g.* that involving the β-hydroperoxy oxygen (−O−O−H) with the consequent formation of a 1,2-dioxoethane derivative.

Table 4. Relevant endocyclic and exocyclic torsion angles (°) (e.s.d.s 0.3—0.4°). The sign convention is such that the sign is positive if a clockwise rotation is required of atom (1) to eclipse atom (4) whilst looking down the (2)–(3) bond

C(10)–C(5)–C(6)–C(7)	–38.6	C(7)–C(8)–C(9)–C(10)	–49.2	C(11)–C(7)–C(8)–C(9)	–128.7
C(9)–C(10)–C(5)–C(6)	15.3	C(9)–C(8)–O(1)–C(12)	133.0	C(6)–C(7)–C(11)–C(13)	60.7
C(5)–C(6)–C(7)–C(8)	50.3	C(13)–C(11)–C(12)–O(1)	–177.2	C(8)–C(7)–C(11)–C(13)	–177.7
C(6)–C(7)–C(8)–O(1)	114.5	O(3)–C(5)–C(6)–C(7)	140.3	O(1)–C(8)–C(9)–C(10)	–168.7
C(6)–C(7)–C(11)–C(12)	–117.1	O(3)–C(5)–C(10)–C(9)	165.7	C(8)–C(9)–C(10)–C(5)	59.9
C(8)–C(7)–C(11)–C(12)	4.5	C(5)–C(6)–C(7)–C(11)	166.7	O(2)–C(12)–O(1)–C(8)	174.1
		H(7)–C(7)–C(11)–C(13)	–59(2)		
(ω_1) C(8)–O(1)–C(12)–C(11)	6.1	(ω_4) C(9)–C(8)–C(7)–C(6)	6.4	C(8)–O(1)–C(12)–C(11)	6.1
(ω_2) C(13)–C(11)–C(12)–O(2)	2.6	C(7)–C(11)–C(12)–O(2)	–179.5	C(7)–C(8)–O(1)–C(12)	9.0
(ω_3) C(11)–C(7)–C(8)–O(1)	–7.8	O(1)–C(12)–C(11)–C(7)	–0.8	C(11)–C(7)–C(8)–O(1)	–7.8

observed and corrected for background and Lorentz-polarization effects.[23]

Structure Solution and Refinement.—For all subsequent computations use was made of the SHELXTL system.[24] The solution was attained with the program RANT [25] assigning random phases to the 192 largest E's (2 330 triple-phase relationships). All 19 non-hydrogen atoms were located on the E-map showing the best figures of merit. The refinement was by standard least-squares methods. The H-atoms were located on a difference Fourier map at an advanced stage of the aniso-tropic refinement. Whilst the H-atoms of the two methyl groups were forced to ride on the bonded C-atoms, the co-ordinates of the other hydrogens were refined under the con-straint C–H = 0.96 ± 0.02 Å. Four different variable aniso-tropic thermal parameters were refined for the –CH, –CH₂, =CH₂ and –CH₃ groups; the last parameter was kept fixed at 0.11 Å² in the final cycles and the others converged to 0.037(5), 0.057(3), and 0.058(6) Å² respectively. The weighting scheme introduced in the final cycles was: $w = 1/[\sigma^2(F_0) + GF_0^2]$, where σ is the standard deviation of F_0 based on counting statistics and G is a variable to be adjusted after each cycle in order to render the $\Sigma w(\Delta F)^2$ as constant as possible over groups of reflexions batched in several ways. The final value of G was 0.000 37. Convergence (mean shift/error $\simeq$ 0.06) was attained at $R = 0.046$, $wR = 0.044$, goodness of fit = 1.471 for 1 047 reflexions and 225 least-squares parameters. Eight reflexions were, in fact, discarded in the course of the refinement because of poor F_0 vs. F_c agreement. The highest peaks in the final difference map were <0.3 e Å⁻³.

Table 2 lists the final parameters of the non-hydrogen atoms, Table 3 the bond distances and angles, and Table 4 relevant endocyclic and exocyclic torsion angles. The Tables of observed and calculated structure factors, anisotropic thermal parameters of the non-hydrogen atoms and of the hydrogen atoms parameters have been deposited as Supple-mentary Publication No. 23703 (9 pp.).*

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