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Douglas Fir Tussock Moth Pheromone: Identification of a Diene Analogue of the Principal Attractant and Synthesis of Stereochemically Defined 1,6-, 2,6-, and 3,6-Heneicosadien-11-ones

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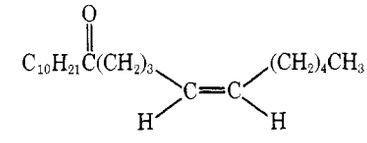
A diene analogue of the principal Douglas fir tussock moth sex pheromone (*Z*)-6-heneicosen-11-one has been isolated and identified as a 1,6-heneicosadien-11-one using mass spectrometry, microozonolysis, and gas chromatography. Five geometric and positional heneicosadien-11-one isomers were synthesized for chromatographic and spectroscopic comparison and for biological testing. Unambiguous structural assignments of the five isomers were established by capillary column gas chromatography, carbon magnetic resonance spectroscopy, infrared and laser Raman spectroscopy, and mass spectrometry.

The principal attractant of the sex pheromone system of the Douglas fir tussock moth (DFTM), *Orgyia pseudotsugata* (McDunnough), was identified as (*Z*)-6-heneicosen-11-one (**1**),[1] synthesized,[2-4] and successfully tested in laboratory and field bioassays.[5] We have now detected a closely related compound in attractive extracts of DFTM female abdominal tips and identified it as a 1,6-heneicosadien-11-one **2** or **3**. Both isomers (*Z*)-1,6-heneicosadien-11-one (**2**) and (*E*)-1,6-heneicosadien-11-one (**3**) have been synthesized for comparison with the natural material and for biological evaluation. In addition, the isomers (*E,Z*)-2,6-heneicosadien-11-one (**4**), (*Z,Z*)-3,6-heneicosadien-11-one (**5**), and (*E,Z*)-3,6-heneicosadien-11-one (**6**) were also synthesized, characterized, and evaluated for attractiveness to DFTM males.

Isolation and Structure Elucidation

The dienone was first observed by gas chromatography–mass spectrometry (GC/MS) studies of partially purified fractions obtained by dry column chromatography[1] of active DFTM extracts. Its mass spectrum is very similar to that of the principal attractant (**1**, Figure 1a) and corresponds to a diene analogue of **1**. Thus the molecular ion (*m/e* 306) established the probable empirical composition as $C_{21}H_{38}O$ and a cleavage ion at *m/e* 169 established the presence of a carbonyl at C-11 and a ten-carbon saturated alkyl chain. The other carbonyl α cleavage ion at *m/e* 165 confirmed assignment of both sites of unsaturation to the remaining ten-carbon alkyl chain. Furthermore, the appearance of an ion at *m/e* 122 (corresponding to the ion at *m/e* 124 in the spectrum of **1**, see Figure 1a), derived via a McLafferty rearrangement with charge retention on the hydrocarbon fragment, strongly suggested that one double bond was at position six[1] and the second double bond was contained in the five-carbon terminus of the alkyl chain (i.e., at positions 1, 2, or 3, see the spectra in Figures 1b, 1c, and 1d).

Isolation of the diene was undertaken from the dichloromethane extract of 1000 crushed DFTM female abdominal



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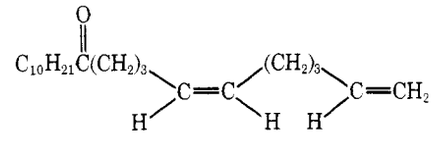

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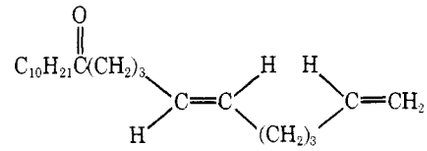

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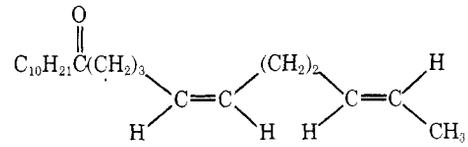

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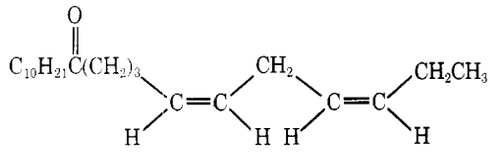

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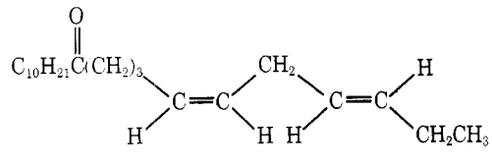

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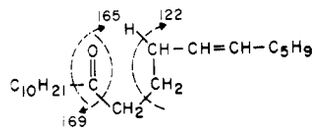


tips. Dry column chromatography on neutral alumina followed by preparative gas liquid chromatography produced a sample (<2 μg) which was subjected to chemical and chromatographic examination. Reductive ozonolysis of the isolated dienone followed by GC/MS analysis (OV-17 column) showed essentially one component which exhibited a retention time and mass spectrum establishing its structure as 5-ketopentadecanal, a sample of the latter being obtained for comparative analysis by ozonolysis of **1**.[1] A second GC/MS analysis of an ozonolysis product mixture (Porapak PS column) again revealed a single, but different, compound. This compound was identified as glutaric dialdehyde, establishing that the two sites of unsaturation in the diene are separated by three methylene units. These results established all features of the dienone structure (a 1,6-heneicosadien-11-one) except the stereochemistry about the C-6,7 double bond, i.e., the diene is either **2** or **3**. Unfortunately, definitive determination of the double bond stereochemistry must await isolation of an additional, adequately pure sample for chromatographic comparison with synthetic dienones **2** and **3**; despite a number of attempts we have not succeeded in obtaining an adequate sample.

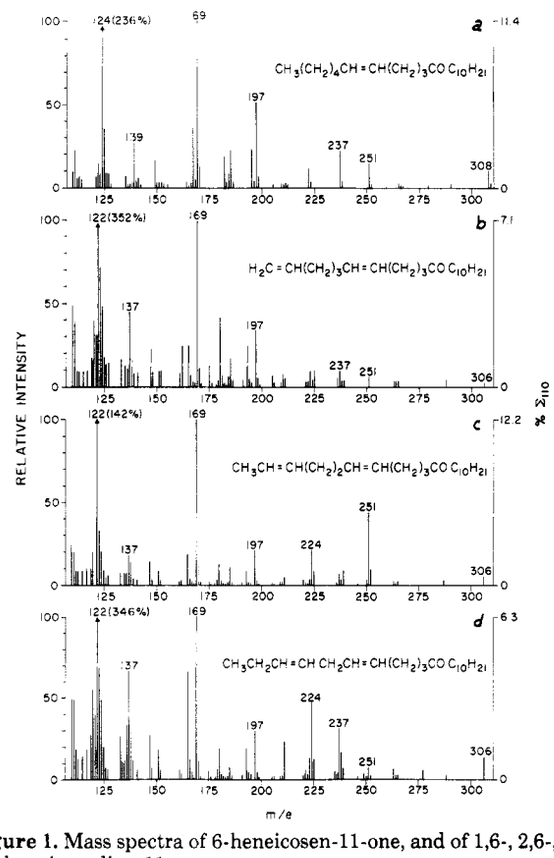
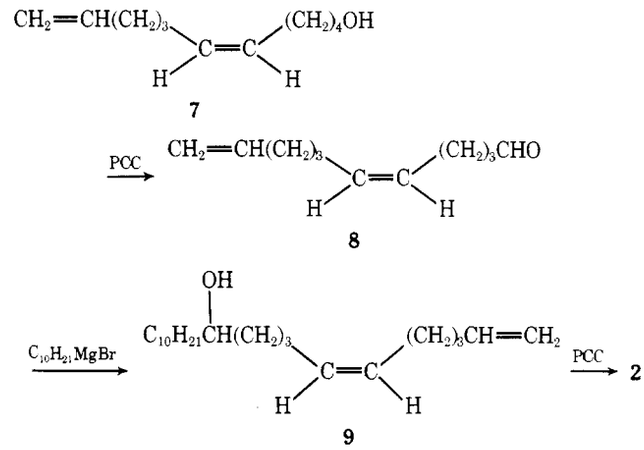


Figure 1. Mass spectra of 6-heneicosen-11-one, and of 1,6-, 2,6-, and 3,6-heneicosadien-11-ones.

Synthesis

Determination of the double bond stereochemistry of the DFTM dienone requires the availability of the two alternative stereoisomers **2** and **3**. Furthermore, the limited supply of material isolated from the insect extract prompted the syntheses of double bond position isomers **4**–**6** of the dienone for comparative chromatographic, spectrometric, and bioassay studies.

The key synthetic intermediate in each sequence was an 11-carbon dienol possessing the desired double-bond placement and stereochemistry. Thus, oxidation of (*Z*)-1,6-undecadien-11-ol (**7**) with pyridinium chlorochromate (PCC)[6] to the corresponding aldehyde (**8**) followed by reaction with *n*-decylmagnesium bromide yielded the 21-carbon dienol **9**



which was again oxidized to produce (*Z*)-1,6-heneicosadien-11-one (**2**).

The preparation of **7** was accomplished in good yield by coupling 5-bromo-1-pentene with the dilithium derivative of 1-hexyn-5-ol (or the corresponding *O*-tetrahydropyranyl derivative[7]) followed by syn hydrogenation of the acetylenic bond over modified P-2 nickel catalyst.[8] A similar sequence employing anti hydrogenation with $Na/NH_3/Et_2O$[9] yielded (*E*)-1,6-undecadien-11-ol, which was subsequently converted to **3**. Synthesis of (*E,Z*)-2,6-heneicosadien-11-one (**4**) was carried out in a sequence analogous to that for **2** and **3**. Somewhat more difficult were the syntheses of (*Z,Z*) and (*E,Z*)-3,6-undecadien-11-ols, precursors to **5** and **6**, respectively. For these syntheses, (*Z*)- and (*E*)-1-bromo-2-pentenes (**10**) were prepared and coupled with copper acetylide **11** in dimethylformamide solution containing sodium cyanide.[10] The coupling reaction yielded a mixture of undecenynols **12** and **13** in which the desired product (**12**) predominated in a ratio of 4:1 over the product of allylic rearrangement (**13**). This represents the first application of this newly developed coupling procedure in pheromone synthesis and, although the specificity of the reagent toward allylic halides is attractive, the production of an unwanted structural isomer (**13**) to such

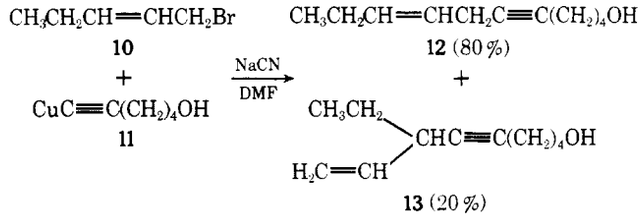


Table I. Gas Chromatographic Selectivities toward Heneicosenones and Heneicosadienones[d]

Column	Relative adjusted retention volumes[d]						
	(*E*)-6[2]	(*Z*)-6- (1)	(*E*)-1,6- (3)	(*Z*)-1,6- (2)	(*E,Z*)-2,6- (4)	(*E,Z*)-3,6- (6)	(*Z,Z*)-3,6- (5)
Support-bonded PEG 20M[a]	1.03	1.00	1.16	1.11	1.15	1.14	1.15
Cyanosilicone (packed)[b]	1.00	1.00	1.25	1.25	1.23	1.20	1.30
Cyanosilicone (capillary)[c]							
Column 1		1.00	1.29		1.23	1.27	1.32
Column 2	0.98	1.00	1.23	1.25			

[a] 80/100 Chromosorb W, 6 ft × 2 mm i.d. stainless steel, 160 °C. [b] 10% on 100/120 Gas Chromosorb Q, 10 ft × mm i.d. stainless steel, 200 °C. [c] Glass capillary columns, 60 m × 0.25 mm i.d., 170 °C. [d] Registry No.—**1**, 54844-65-4; **2**, 65956-73-2; **3**, 65956-72-1; **4**, 65956-74-3; **5**, 65956-76-5; **6**, 65956-75-4.

an extent leads us to conclude that syntheses of skipped methylene enynes may be accomplished more efficiently using the acetylene Grignard/CuCl system.[11,12]

Gas Chromatographic Analyses

Partial resolution of synthetic (*E*)- and (*Z*)-1,6-dienones (**2** and **3**) was possible using a glass capillary column coated with a cyanopropyl silicone polymer and using a packed column of annealed, support-bonded polyethylene glycol 20M. The best resolution of the (*E*)- and (*Z*)-1,6-dienones (**2** and **3**) and of the dienone positional and geometric isomers (**4–6**) was observed on the capillary column due to the much greater efficiency relative to the packed columns. Only the (*Z*)-1,6 dienone (**2**) was adequately resolved from the other four dienones on the support-bonded 20M column, and only the (*Z,Z*)-3,6 dienone (**5**) was resolved from the other dienones on a packed column of a cyanopropylsilicone phase. Table I records the selectivities of these columns toward the monoenones and dienones (**1–6**).

Spectrometric Studies

Synthetic dienones **2–6** were examined by a variety of spectrometric methods which served to unambiguously establish their structures.

Mass Spectra. Mass spectra of the three double bond position isomers are shown in Figure 1. Although mass spectrometry is not a reliable method for determining the positions of carbon–carbon double bonds[13] unless the double bond is specifically modified,[14] comparison of the spectra of the dienone positional isomers **1b–d** with that of the DFTM dienone permits the latter to be assigned correctly as a 1,6-dienone. Although the spectra of the three positional isomers show the same *m/e* values for nearly all their fragmentation and rearrangement products, significant differences are apparent in relative ion abundances.

Carbon Magnetic Resonance Spectra. Carbon magnetic resonance spectra were obtained for isomeric dienones **2, 3, 4,** and **6.** The chemical shifts and assignments are listed in Table II. The assignments were made by comparison with literature values[15–20] and are not rigorously established. Comparison of the ^{13}C NMR spectra of the (*Z*)-1,6 and (*E*)-1,6-dienones (**2** and **3**, respectively) shows differences which are characteristic of opposite geometries at the six position double bond. The olefinic carbons of the *E* double bond are deshielded by 0.5 ppm or more with respect to those of the *Z* isomer.[15–20] The observed line shift (from 26.6 ppm for the *Z* isomer to 31.9 ppm for the *E* isomer) for carbons 5 and 8 is characteristic of these allylic carbons.[15–17,19]

In the spectrum of (*E,Z*)-2,6-heneicosadien-11-one (**4**), the chemical shifts of carbon one (17.96 ppm), of carbon two (124.9 ppm), and of carbon four (32.56 ppm) are characteristic of an *E* olefin at position two.[16,18,19] The chemical shifts of carbons six and seven are essentially the same as those for the (*Z*)-1,6-dienone and thus consistent with a *Z* double bond at position six. Likewise, the assigned shifts of allylic carbons five (27.29 ppm) and eight (26.59 ppm) further support the *Z* geometry.

The spectrum of (*E,Z*)-3,6-heneicosadien-11-one (**6**) is similarly characteristic. The chemical shift of carbon two (25.59 ppm) as well as the absence of a line at about 20 ppm (expected for a (*Z*)-3 double bond) and the chemical shift of carbon three (132.2 ppm) are consistent with an *E* geometry at position three.[16,17] The apparent shielding of carbon 6 (relative to similar carbons of the 1,6- and 2,6-dienones **2, 3,**

Table II. ^{13}C Nuclear Magnetic Resonance Chemical Shifts for Isomeric Heneicosadien-11-ones

Carbon type[a]	^{13}C NMR resonances, δ_{Me_4Si} (C position no.)			
	(*Z*)-1,6(**2**)	(*E*)-1,6(**3**)	(*E,Z*)-2,6(**4**)	(*E,Z*)-3,6(**6**)
Olefinic C	138.5 (2)	138.6 (2)	130.5 (3)	132.2 (3)
	130.2, 128.9 (6, 7)	130.7, 129.5 (6, 7)	130.0, 128.8 (6, 7)	129.0, 128.6 (4, 7)
	114.3 (1)	114.2 (1)	124.9 (2)	127.0 (6)
Allylic CH_2	33.28 (3)	33.13 (3)	32.56 (4)	30.36 (5)
	26.58 (5, 8)	31.92 (5, 8)	27.29 (5)	26.49 (8)
			26.59 (8)	25.59 (2)
α-Carbonyl CH_2	42.83, 41.96 (10, 12)	42.86, 41.87 (10, 12)	42.76, 41.96 (10, 12)	42.85, 41.96 (10, 12)
Other CH_2	31.85 (19)	31.92 (19)	31.84 (19)	31.94 (19)
	29.45, 29.29, 28.87 (4, 9, 15–18)	29.45, 29.29, 28.67 (4, 9, 15–18)	29.45, 29.28 (9, 15–18)	29.41 (9, 15–18)
	23.80, 23.65, 22.63 (13, 14, 20)	23.82, 23.52, 22.65 (13, 14, 20)	23.81, 23.62 (13, 14)	23.90, 23.61, 22.71 (13, 14, 20)
Methyl	14.21 (21)	14.09 (21)	17.96 (1)	14.19 (21)
			14.09 (21)	13.89 (1)

[a] Carbonyl carbon chemical shifts were not determined.

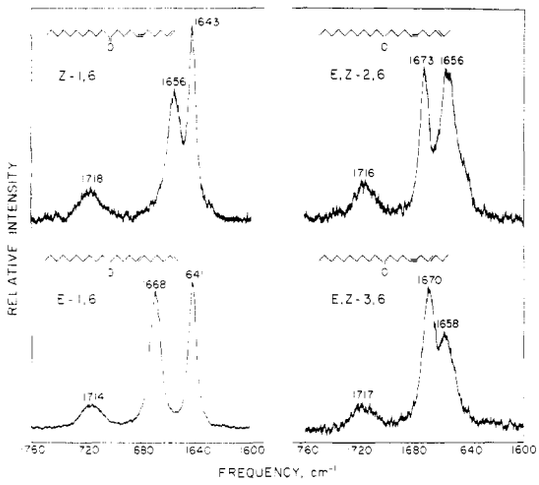


Figure 2. Laser Raman spectra of heneicosadien-11-ones (**2, 3, 4,** and **6**) in the carbonyl and olefinic double bond stretching region.

and **4**) is consistent with the skipped methylene structure.[16,17] In the spectrum of **6**, the double allylic carbon five has a chemical shift of 30.36 ppm which is expected for an *E,Z* skipped methylene;[16,18] no absorption in this region is observed in the other three spectra. The shift of carbon eight (26.49 ppm) agrees with a *Z* geometry of the double bond at position six.

Vibrational Spectra. The laser Raman spectra of the heneicosadien-11-ones (Figure 2) provide unambiguous characterization of their olefinic bond geometries. The structurally sensitive C=C stretching vibrations lie in the 1640–1675-cm^{-1} region,[21] while the carbonyl vibrations for all isomers were observed at 1716 ± 2 cm^{-1}. For the terminal double bonds of the (*Z*)-1,6 and (*E*)-1,6 isomers (**2** and **3**, respectively), strong and symmetrical peaks were recorded at 1642 ± 1 cm^{-1}. The (*Z*)-6 C=C absorptions appear to be somewhat less intense and lie at ~1656 cm^{-1}. (The reference compounds (*E*)- and (*Z*)-6-heneicosen-11-ones[2] exhibit single, symmetrical peaks at 1668 and 1654 cm^{-1} due to the *E* and *Z* double bonds, respectively, and peaks at ~1715 cm^{-1} due to the carbonyl vibrations.) Slightly greater variation in peak position was observed for the *E* double bonds, giving rise to peaks between 1668 and 1673 cm^{-1}. These vibrational bands are similar in intensity and shape to the terminal bond vibrations. All Raman frequencies in this spectral region were strongly polarized, as expected.

Infrared spectra of these compounds were studied in the structurally sensitive in-phase, out-of-plane CH wagging region near 970 cm^{-1} for trans-disubstituted hydrocarbon olefins.[22] The (*E*)-1,6(**2**), (*E,Z*)-2,6(**4**), and (*E,Z*)-3,6(**6**) isomers showed moderately strong absorptions at 968, 959, and 965 cm^{-1}, respectively; however, no such band could be observed in this region for the (*Z*)-1,6 isomer (**2**), further confirming the structural identities of these compounds.

Biological Activity. Laboratory bioassays[1,5] of the isolated DFTM dienone and laboratory and field bioassays of the synthetic (*Z*)-1,6-dienone (**2**) and (*E,Z*)-3,6-dienone (**6**) showed these compounds to be attractive to DFTM males; dienones **3–5** exhibited little or no attractiveness. A more detailed study of the biological activities of the synthetic dienones will be the subject of a separate report.

Experimental Section

Partial purification of insect extracts[1] was carried out by chromatography (dry column or TLC) with benzene on alumina (activity III), R_f 0.8. Further purification was accomplished by trapping of components during elution from gas chromatography (GC) (Apolar 10C column) using glass capillaries along which a thermal gradient was established.[23] Collected material was washed from the capillaries with CH_2Cl_2 into conical vials and was ozonized at −70 °C.[24] Efforts were unsuccessful to develop a procedure for the GC analysis of low molecular weight aldehydes (at levels less than 100 ng from ozonolysis) as their 2,4-dinitrophenylhydrazones.[25] GC analyses were made on OV-101, OV-17, and Carbowax 20M columns (1.5 to 3% on 80/100 Chromosorb W, AW-DMCS, 6 ft × 2 mm i.d., glass and stainless steel), on an Apolar 10C column (10% on 100/120 Gas-Chromosorb Q, 10 ft × 2 mm i.d., stainless steel), on a Porapak PS column (80/100, 6 ft × 2 mm i.d., glass), and on glass capillary columns (0.25 mm i.d., 60 m SP 2340, 30 m FFAP, and 10 m SE30, J&W Scientific, Inc.) using flame ionization detection. Analytical high pressure liquid chromatography (HPLC) with $AgNO_3$-impregnated silica gel was carried out on a 20 × 0.6 cm column packed with 5% $AgNO_3$/silica gel + LiEF54 using benzene,[26] and preparative HPLC utilized a 25 × 2.45 cm column packed with 20% $AgNO_3$/silica gel.[26] ^1H NMR spectra were obtained with a Varian HA-100 spectrometer usually with a lock on benzene in 10% C_6H_6/CCl_4 solutions. ^{13}C NMR spectra were obtained using a Varian XL-100 spectrometer, and IR Spectra using a Perkin-Elmer 621 spectrometer. Mass spectra were obtained using a DuPont 21-491B GC/MS system, and the mass spectra of the positional isomers of the dienones shown in Figure 1 were all recorded within a 30 min period under identical operating conditions. Raman spectra were recorded on a Jarrell-Ash 25–300 spectrophotometer equipped with an RKB, Inc. digital grating drive. Excitation at 514.5 nm was obtained from a Coherent Radiation Model 52 MG Ar/Kr laser. Throughout the syntheses described below, analyses by GC/MS were made and were consistent with the indicated conversions.

Preparations of Pentenols. 2-Pentyn-1-ol was prepared by the coupling of propargyl alcohol with bromoethane using $LiNH_2/NH_3$.[27] (*Z*)-2-Penten-1-ol was synthesized by syn hydrogenation of 2-pentyn-1-ol using P-2 nickel modified with ethylenediamine (P-2 Ni/EDA) at 30 to 40 psi H_2 in methanol for 7 to 10 h[28] (mole ratio catalyst/acetylenic compound-1/20).[8] GC analyses (OV-101 and Apolar 10C columns) showed no acetylenic compound remaining and 1 to 3% *n*-pentanol; resolution of the *E* and *Z* isomers of 2-penten-1-ol was not attained on these columns. Anti hydrogenations of 2-pentyn-1-ol and of commercial 2-pentyn-5-o1 (Chem Samples Co.) were carried out with $Na/NH_3/Et_2O$ over 4 to 6 h.[9] GC analyses (OV-101, Apolar 10C, and Porapak PS columns) showed no pentanol or acetylenic starting materials and, in the case of the (*E*)-2-penten-5-ol, no *Z* isomer.

Preparations of Bromopentenes. The pentenols were converted to the corresponding bromopentenes with either of two reagents: PBr_3/pyridine (catalytic amount)/Et_2O[29,30] or Ph_3PBr_2/pyridine/CH_2Cl_2.[31] Conversions with the latter reagent involved 1 equiv of the alcohol, 1.1 equiv of Ph_3PBr_2, and 1.1 equiv of pyridine in CH_2Cl_2, initially at 0 °C followed by gradual warming to 25 °C. The crude product was distilled from the reaction mixture under reduced pressure and purified by fractional distillation. In each of the reactions of Ph_3PBr_2 with (*Z*)-2-penten-1-ol and 1-penten-5-ol, one product only was detected by GC analyses in each case, the isolated yield in the latter reaction being 89%. Using the reagent PBr_3/pyridine/Et_2O, the isolated yields were usually about 50%, and the conversions were often accompanied by side reactions. Significant amounts of HBr addition products were observed using PBr_3 in the syntheses of the 5-bromo-2-pentenes (up to 15%) and of 5-bromo-1-pentene (20 to 40%). *Z* to *E* isomerization of the double bond was observed in the conversion of (*Z*)-2-penten-1-ol to the bromopentene with PBr_3 (~50% isomerization). Another side reaction observed in the latter conversion was S_N2' displacement which produced 3-bromo-1-pentene (10%). These side reactions were not observed when Ph_3PBr_2 was used. Partial resolution of 3-bromo-1-pentene, 1-bromo-(*E*)-2-pentene, and 1-bromo-(*Z*)-2-pentene was possible using a packed OV-17 column (6 ft. × 2 mm i.d., glass), and complete resolution was attained on a glass capillary column coated with SE-30 column (10 m × 0.25 mm i.d.).

5-Bromo-1-pentene: bp ~70 °C (140 mm); NMR (10% C_6H_6/CCl_4) δ 5.87–5.48 (m, 1), 5.12–4.90 (m, 2), 3.23 (t, 2), 2.08 (m, 2), 1.85 (m, 2). **5-Bromo-(*Z*)-2-pentene:** NMR (CCl_4) δ 5.78–5.18 (m, 2), 3.28 (t, 2), 2.62 (g, 2), 1.66 (d, 3); IR (film, KBr) 3024, 2970, 2924, 2865, 1654, 1435, 1268, 1255, 1207, 1030, 966, 702 cm^{-1}; laser Raman (neat) 1655 cm^{-1} (intense, symm). **5-Bromo-(*E*)-2-pentene:** NMR (CCl_4) δ 5.56–5.32 (m, 2), 3.28 (t, 2), 2.51 (t, 2), 1.67 (d, 3); IR (film, KBr) 3030, 2967, 2940, 2910, 2858, 1735, 1438, 1374, 1255, 1204, 1054, 964 cm^{-1}; laser Raman (neat) 1669 cm^{-1} (intense, symm). **1-Bromo-(*Z*)-2-pentene:** bp 75 °C (135 mm); NMR (10% C_6H_6/CCl_4) δ 5.74–5.36 (m, 2), 3.85 (d, 2), 2.10 (m, 2), 0.98 (t, 3). **1-Bromo-(*E*)-2-pentene:** bp 80 °C (144 mm); NMR (10% C_6H_6/CCl_4) δ 5.76–5.58 (m, 2), 3.84 (d, 2), 2.24–1.88 (m, 2), 0.94 (t, 3).

Preparations of Undecenynols. (*E*)-2-Undecen-6-yn-11-o1 (as

the THP derivative) was synthesized by the coupling of 5-(2'-tetrahydropyranyloxy)-1-hexyne[28] with 5-bromo-(*E*)-2-pentene using *n*-butyllithium in THF/hexane/hexamethylphosphoramide (HMPA).[7] 2-Undecen-6-yn-11-ol was synthesized by the coupling of 5-bromo-1-pentene with the dilithium adduct of 1-hexyn-6-ol in THF/hexane/HMPA. The tetrahydropyranyl derivative of 1-hexyn-6-ol was initially employed in the coupling reaction (75% yield); in later syntheses the dilithium adduct was used without complication. Two molar equivalents of *n*-BuLi (2.5 M in hexane) were added slowly to a 0.25 M solution of 1-hexyn-6-ol in dry THF at about −30 °C under dry nitrogen. Precipitation of a colorless solid at times required the addition of more THF to maintain efficient stirring. After 5 min, a volume of HMPA was added equal to one-fourth that of the reaction, and the resulting mixture was cooled to about −70 °C. One molar equivalent of 5-bromo-1-pentene (in a volume of HMPA equal to that added initially) was added and the cold bath was removed. Gradual warming of the stirred mixture to 25 °C produced a colorless solution. GC analysis (6 ft OV-101) of a quenched aliquot showed no starting materials and one product. The reaction solution was reduced in volume by ⅔, quenched with two volumes of H_2O, and extracted with hexane. After drying, fractional distillation (bp 90 °C (0.4 mm)) yielded the pure product, (*E*)-2-undecen-6-yn-11-ol (67%).

(*Z*)- and (*E*)-3-undecen-6-yn-11-ols were synthesized by the coupling of 1-bromo-(*Z*)-2-pentene and of 1-bromo-(*E*)-2-pentene with the copper acetylide of 1-hexyn-6-ol (**11**) in DMF/NaCN.[10] The method of in situ generation of the copper acetylide[33] was ineffective in our hands. Instead, the reagent (**11**) was synthesized separately,[34] dried, and then coupled with the allylic bromides. GC/MS analyses (OV-101 and Apolar 10C columns) of the hexane extracts of the reaction mixture showed no allylic bromide and two higher boiling products, the undecenynol (**12**) and 3-ethyl-1-nonen-4-yn-9-ol (**13**), 80 and 20%, respectively. Fractional distillation (85 °C (5 μm)) using a 30-cm Dufton column with a spiral of Nichrome wire gave a pure sample of **13** and a sample of 90% pure 3-undecen-6-yn-11-ol (**12**). Attempts to separate the two compounds by preferential reaction with bis(3-methyl-2-butyl)borane (disiamylborane)[35] or by preferential complexation with $CaCl_2$[36] were unsuccessful; in both procedures, the two compounds exhibited essentially equal reactivities.

1-Undecen-6-yn-11-ol: bp ~90 °C (0.4 mm); NMR (10% C_6H_6/CCl_4) δ 5.96–5.52 (m, 2), 4.10–3.86 (m, 2), 3.52 (br t, 2), 3.36 (br s, 1), 2.26–1.98 (m, 6), 1.70–1.42 (m, 6). **11-(2'-Tetrahydropyranyloxy)-1-undecen-6-yne:** bp 100 °C (5 μm); NMR (10% C_6H_6/CCl_4) δ 5.96–5.52 (m, 1), 5.12–4.84 (m, 2), 4.50 (m, 1), 3.88–3.54 (m, 2), 3.52–3.16 (m, 2), 2.26–1.98 (m, 6), 1.80–1.36 (m, 12). **11-(2'-Tetrahydropyranyloxy)-(*E*)-2-undecen-6-yne:** bp ~100 °C (10 μm); NMR (CCl_4) δ 5.50–5.32 (m, 2), 4.50 (m, 1), 3.82–3.54 (m, 2), 3.52–3.20 (m, 2), 2.13 (s, 6), 1.76–1.42 (m, 12). **(*E*)-3-Undecen-6-yn-11-ol:** bp ~80 °C (5 μm); NMR (10% C_6H_6/CCl_4) δ 5.84–5.16 (m, 2), 3.52 (t, 2), 3.26 (br s, 1), 2.88–2.74 (m, 2), 2.26–2.06 (m, 2), 2.06–1.90 (m, 2), 1.68–1.46 (m, 4), 0.96 (t, 3). **3-Ethyl-1-nonen-4-yn-9-ol:** NMR (10% C_6H_6/CCl_4) δ 5.88–5.50 (m, 1), 5.34–4.90 (m, 2), 3.52 (br t, 2), 3.14 (br s, 1), 3.04–2.78 (m, 1), 2.32–2.10 (m, 2), 1.74–1.38 (m, 6), 0.96 (t, 3).

Preparations of Heneicosadien-11-ones. The conversions of the hendecenyn-1-ols to the heneicosadien-11-ones were all carried out in essentially identical reaction sequences. The former compounds were syn hydrogenated with P-2 Ni/EDA[8] and anti reduced with $Na/NH_3/Et_2O$.[9] The resulting undecadien-1-ols were oxidized to the corresponding aldehydes with pyridinium chlorochromate (PCC).[6] Subsequent reaction with *n*-decylmagnesium bromide (iodide was less effective) in ether followed by oxidation of the resulting alcohol (heneicosadien-11-ol) with PCC yielded the crude heneicosadien-11-one. The product was purified by column chromatography on neutral silica gel using 15% CH_2Cl_2 in hexane. Throughout these conversions, GC/MS analyses confirmed the nearly quantitative conversions (1.5% OV-101, 6 ft. × 2 mm id, glass).

The catalytic hydrogenation of the acetylenic bond of 10-undecen-5-yn-1-ol with P-2 Ni/EDA required more carefully controlled conditions; the terminal olefinic bond apparently exhibited a significant degree of reactivity. The reduction was carried out at atmospheric pressure and was discontinued after 95 to 100% of 1 equiv of H_2 had been consumed. GC/MS analysis showed 5% starting material, 5% of a monounsaturated alcohol ($C_{11}H_{22}O$), and 90% (*Z*)-2,6-undecadien-11-ol. Under increased pressure (30–40 psi), considerably more monounsaturated alcohol was produced. Distillation of the reaction mixture (20 cm Vigreaux column, 70 °C (3 μm)) did not appreciably improve the purity of the dienol. The oxidations with PCC were carried out at 25 °C in CH_2Cl_2. The resulting black sludge was washed with CH_2Cl_2; the CH_2Cl_2 solution was reduced to a small volume and diluted with five times its volume of hexane and passed through Celite, to give a nearly colorless solution. The preparation of (*Z,Z*)-3,6-heneicosadien-11-one (**5**) produced a large amount of *E,Z* isomer (**6**) due to the *Z* to *E* isomerization during the preparation of the bromopentene. High-pressure liquid chromatography of the mixture on $AgNO_3$/silica gel produced a purified sample of the *Z,Z* isomer (**5**). Unfortunately, during the final workup step, microflash distillation, the sample underwent appreciable pyrolysis so that milligram quantities of this isomer were not available for NMR or IR. **(*Z*)-1,6-Heneicosadien-11-one (2):** liquid; NMR (10% C_6H_6/CCl_4) δ 6.05–5.60 (m, 1), 5.37 (m, 2), 5.10–4.90 (m, 2), 2.38 (t, 4), 2.20–1.90 (m, 6), 1.75–1.40 (m, 6), 1.26 (s, 14), 0.88 (t, 3); IR (film, KBr) 3080, 3003, 2930, 2856, 1712, 1637, 1455, 1408, 1365, 987, 907 cm^{-1}; laser Raman (neat) 1718, 1656, 1643 cm^{-1}. **(*E*)-1,6-Heneicosadien-11-one (3):** mp 30 °C; NMR (10% C_6H_6/CCl_4) δ 6.05–5.60 (m, 1), 5.37 (m, 2), 5.10–4.90 (m, 2), 2.38 (t, 4), 2.20–1.90 (m, 6), 1.75–1.40 (m, 6), 1.26 (s, 14), 0.88 (t, 3); IR (film, KBr) 3080, 2930, 2860, 1712, 1639, 1455, 1438, 1410, 1367, 990, 968, 909 cm^{-1}; laser Raman (neat) 1714, 1668, 1641 cm^{-1}. **(*E,Z*)-2,6-Heneicosadien-11-one (4):** liquid; NMR (10% C_6H_6/CCl_4) δ 5.54–5.30 (m, 4), 2.39 (t, 4), 2.05 (br s, 6), 1.76–1.50 (m, 6), 1.26 (s, 14), 0.88 (t, 3); IR (film, KBr) 3004, 2850, 2754, 1710, 1650, 1454, 1365, 959 cm^{-1}; laser Raman (neat) 1716, 1673, 1656 cm^{-1}. **(*E,Z*)-3,6-Heneicosadien-11-one (6):** liquid; NMR (10% C_6H_6/CCl_4) δ 5.46–5.24 (m, 4), 2.68 (br t, 2), 2.25 (t, 4), 2.10–1.88 (m, 4), 1.72–1.40 (m, 4), 1.26 (s, 14), 0.96 (t, 6); IR (film KBr) 3007, 2960, 2858, 1715, 1458, 1409, 1370, 965 cm^{-1}; laser Raman (neat) 1717, 1670, 1658 cm^{-1}.

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Registry No.—(*E*)-**2**, 65956-72-1; **7**, 65956-77-6; **8**, 65956-78-7; **9**, 65956-79-8; (*Z*)-**10**, 7348-78-9; (*E*)-**10**, 7348-71-2; **11**, 65956-80-1; (E)-**12**, 65956-81-2; (*Z*)-**12**, 65956-82-3; **13**, 65956-83-4; 2-pentyn-1-ol, 6261-22-9; (*Z*)-2-penten-ol, 1576-95-0; 2-pentyn-5-ol, 10229-10-4; 1-penten-5-ol, 821-09-0; 3-bromo-1-pentene, 53045-71-9; 5-bromo-1-pentene, 1119-51-3; 5-bromo-(*Z*)-2-pentene, 50273-84-2; 5-bromo-(*E*)-2-pentene, 7515-62-0; (*E*)-2-undecen-6-yn-11-ol THP derivative, 65956-84-5; 1-hexyn-6-ol 2Li salt, 65956-85-6; 1-hexyn-6-ol THP derivative, 1720-37-2; 1-hexyn-6-ol, 928-90-5; (*E*)-2-undecen-6-yn-11-ol, 65956-86-7; (*E*)-2-penten-5-ol, 764-37-4; 1-undecen-6-yn-11-ol, 65956-87-8; 11-(2'-tetrahydropyranyloxy)-1-undecen-6-yn, 65956-88-9; (*E*)-1,6-undecadien-11-ol, 65956-89-0; decyl bromide, 112-29-8.

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Chemiluminescence of 2-(6′-Hydroxy-2′-benzothiazolyl)-4-isopropylidene-Δ^2-thiazolin-5-one, a Byproduct Formed in the Chemiluminescence of a Firefly Luciferin Analogue

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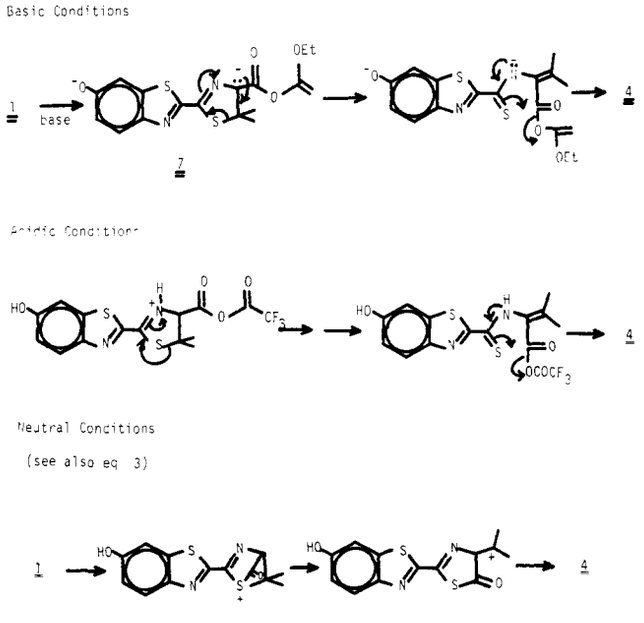
The structure of 2-(6′-hydroxy-2′-benzothiazolyl)-4-isopropylidene-Δ^2-thiazolin-5-one (**4**) is assigned to a byproduct formed in the chemiluminescence of esters of the dimethyl derivative of firefly luciferin (**3**). Compound **4** also proved to be chemiluminescent on reaction with potassium phenoxide and oxygen. Thiazolinecarboxylic acids and thiazolinones are apparently brought into equilibrium by base, and they share a common intermediate in the chemiluminescence reaction.

In studies dealing with the chemi- and bioluminescence of firefly luciferin we reported that the ethoxyvinyl ester of the 5,5-dimethyl derivative of luciferin (**1**) was chemiluminescent on treatment with base and oxygen and that three products were formed: 5,5-dimethyloxyluciferin (**2**) (formed in the excited state), 5,5-dimethylluciferin (**3**) (a hydrolysis product), and a compound analyzing for $C_{13}H_{10}N_2O_2S_2$ (**4**).[1-3] We had earlier proposed, on the basis of preliminary data, that the C_{13} compound was a thiazinone (structure **5**).[1] We now report, with additional evidence, that the C_{13} compound is the isomer 2-(6′-hydroxy-2′-benzothiazolyl)-4-isopropylidene-Δ^2-thiazolin-5-one (**4**).

The proof of structure rests largely on the elemental analysis ($C_{13}H_{10}N_2O_2S_2$) and the formation of acetone on ozonolysis. The mass spectrum showed a parent ion at *m/e* 290, the molecular weight corresponding to the formula given above. The methyl signals in the NMR spectrum, δ 2.45 and 2.51, were similar to the values reported for analogue **6** (δ 2.38 and 2.44).[4] The ultraviolet absorption at 373 nm (in Me_2SO) was consistent with structure **4** in that dimethylluciferin (**3**) absorbs at 330 nm and oxyluciferin **2** absorbs at 390 nm. The infrared absorption at 1660 cm^{-1} (KBr) is consistent with structure **4** (λ_{max} for compound **6** is 1686 cm^{-1} in $CHCl_3$).[4]

Scheme I



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