128.0, 126.0, 124.9, 119.8, 29.8. The $^1$H NMR was as reported.[14]

**Acknowledgment.** We are grateful to the Northwest Area Foundation of the Research Corp. for support of this research and to Catherine Hawtrey for technical assistance.

**Registry No.** **3**, 14503-20-9; **4**, 65774-75-6; **5**, 84040-97-1; **6**, 54290-41-4; **7**, 84040-98-2; **8**, 84040-99-3; **9**, 84041-00-9; **10**, 84041-01-0; **11**, 84041-02-1; **12**, 84041-03-2; **13**, 50919-54-5; **14**, 84041-04-3; **15**, 84041-05-4; **16**, 6827-31-2; **17**, 84041-06-5; **18**, 65957-35-9; DEAD, 762-21-0; butadiene, 106-99-0.

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# Stereochemistry of the Diels–Alder Reaction of Cyclopentadiene and 3,3,3-Trifluoropropene

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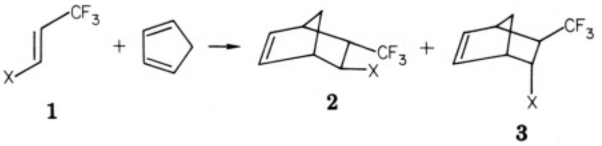
*Received May 28, 1982*

One of the earliest reports of the Diels–Alder reaction notes the preference for endo addition by substituted dienophiles.[1] Alder and Stein first attributed the endo preference to overlap of the $\pi$ system of unsaturated dienophile substituents with the $\pi$ system of the diene[1] and later to overlap of the nonbonded electrons of the substituent with the $\pi$ system of the diene.[2] Since then other investigators have invoked various explanations for the endo preference, including the effect of unsaturated substituents on frontier orbitals,[3–5] steric effects,[6,7] the effect of "strong intermolecular attractive forces",[8] electrostatic effects,[9] or a combination of these effects.[10]

The trifluoromethyl substituent exerts a unique influence on a dienophile since it lacks $\pi$ electrons, yet it exerts an electron-withdrawing effect on a par with that of the usual dienophile substituents. McBee has made an extensive study of the effect of fluorine and fluorinated substituents on the Diels–Alder reaction of cyclopentadiene with olefins[9,11] (eq 1). The case of 3,3,3-trifluoropropene (**1a**) is of particular interest since it shows the influence of the trifluoromethyl group unperturbed by other substituents, but the stereochemical outcome of this reaction was not determined.[11a] We have repeated this reaction and undertaken a more thorough analysis of the results in order to provide firm data on the influence of the trifluoromethyl group on Diels–Alder stereoselectivity.[12]



(1)

**1** **2** **3**

**a**, X = H; **b**, X = CO$_2$H; **c**, X = CO$_2$Et; **d**, X = CH$_2$OH

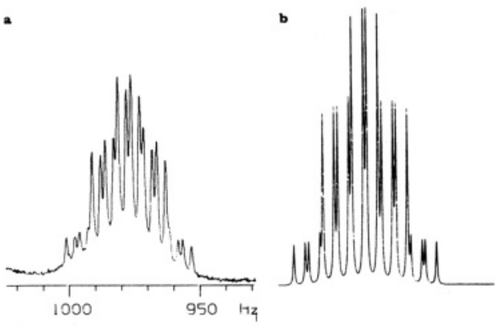


**Figure 1.** (a) 360-MHz $^1$H NMR of the CHCF$_3$ signal of major isomer **2a**. (b) Computer simulation of $^4J$ = 9.6 Hz, $^2J$ = 9.6 Hz, $J$ = 4.8 Hz, and $^2J$ = 3.75 Hz.

When an equimolar mixture of **1a** and cyclopentadiene is heated at 135 °C for 84 h, a 4:1 mixture of two products is observed by $^{19}$F NMR. After removal of unreacted starting materials the mixture is analyzed by 360-MHz $^1$H NMR, which resolves the C**H**CF$_3$ signal of the major isomer and allows all coupling constants for this proton to be determined (Figure 1). The values of $J$ = 9.6 Hz (q), $J$ = 9.6 Hz (d), $J$ = 4.8 Hz (d), and $J$ = 3.75 Hz (d) are consistent with the values predicted for the endo isomer **2a** and inconsistent with those predicted for the exo isomer **3a**.[13]

Experiments have been performed to determine if the observed ratio represents a kinetic or a thermodynamic mixture. Small samples of the reactants are heated at 135 °C for 5, 17, and 40 h; in each case the same 4:1 ratio of products is observed. Small samples of pure **2a** and **3a** are obtained by preparative gas chromatography. These are separately heated at 135 °C for 22 h, whereupon analysis by gas chromatography reveals no isomerization of either sample. Thus, the 4:1 ratio in favor of the endo isomer

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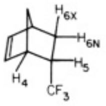
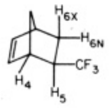
(13) Predicted coupling constants for the endo isomer **2a** are $J_{4\text{-}5}$ = 3–4 Hz, $J_{5\text{-}6X}$ = 9–10 Hz, and $J_{5\text{-}6N}$ = 2.5–5 Hz. For the exo isomer **3a** they are $J_{4\text{-}5}$ = 0–2 Hz, $J_{5\text{-}6X}$ = 2.5–5 Hz, and $J_{5\text{-}6N}$ = 6–7 Hz. In bicyclo[2.2.1]hept-2-enes the exo proton signals appear downfield from the endo proton signals. The signal from the endo H$_5$ of the minor isomer appears to be at $\delta$ 2.01, partially obscured by the signal from H$_{6X}$ of the major isomer at $\delta$ 1.95, but is indeed upfield of the signal from the exo H$_5$ of the major isomer at $\delta$ 2.72. The same argument is used to assign the signals at $\delta$ 1.95 ($J_{6X\text{-}6N}$ = 12 Hz, $J_{6X\text{-}5}$ = 10 Hz, $J_{6X\text{-}1}$ = 3.75 Hz) to H$_{6X}$ and at $\delta$ 1.13 ($J_{6N\text{-}6X}$ = 12 Hz, $J_{6N\text{-}5}$ = 5 Hz, $J_{6N\text{-}1}$ = 2.5 Hz) to H$_{6N}$ of the major isomer and the signals at $\delta$ 1.69 ($J_{6X\text{-}6N}$ = 12 Hz, $J_{6X\text{-}5}$ = 5 Hz, $J_{6X\text{-}1}$ = 3.5 Hz) to H$_{6X}$ and the partly obscured signal at $\delta$ 1.38 to H$_{6N}$ of the minor isomer. The coupling constants which are visible are consistent with the assignments. Gordon, A. J.; Ford, R. A. "The Chemist's Companion"; Wiley: New York, 1972; pp 258, 272, 274.



**2a**



**3a**

**2a** is the kinetic product ratio.

It thus appears that the favored approach of diene and dienophile occurs with the trifluoromethyl group in an endo orientation. While those explanations which invoke $\pi$-orbital overlap do not apply,[1,3a,4,14] the results may be explained by steric interaction between the trifluoromethyl group and the methylene protons of cyclopentadiene in the exo transition state,[6,7,15] electrostatic effects,[9] or secondary orbital overlap effects.[3b,5,16]

## Experimental Section

**General Methods.** The NMR experiments were carried out in chloroform-*d*. The $^{19}$F spectra were obtained on a Varian T-60 spectrometer equipped with a wide-sweep accessory and operating at 56.4 MHz. Chemical shifts are reported in parts per million downfield (negative values upfield) from an external $CFCl_3$ standard; coupling constants are in hertz. The $^1$H NMR spectra were obtained on a Nicolet NIC-360-WB spectrometer operating at 360 MHz in a pulsed Fourier transform mode. Chemical shifts are reported in parts per million downfield from internal tetramethylsilane standard; coupling constants are in hertz. Preparative and analytical gas chromatography were carried out on a Perkin-Elmer 3920B chromatograph utilizing a 2 m × 6 mm column packed with 3% OV-17 on 60/80-mesh Chromosorb W (helium carrier at 60 mL/min) and a thermal-conductivity detector. Cyclopentadiene was prepared by cracking[17] technical grade dicyclopentadiene from Eastman Organic Chemicals; 3,3,3-trifluoropropene was purchased from Fairfield Chemical Co.

***endo*- and *exo*-5-(Trifluoromethyl)bicyclo[2.2.1]hept-2-ene (2a and 3a).** A mixture of 3.3 g (0.05 mol) of freshly cracked, cold cyclopentadiene and 4.8 g (0.05 mol) of condensed 3,3,3-trifluoropropene were combined with 0.05 g of hydroquinone in a heavy-walled Pyrex tube at −78 °C. The tube was sealed and heated in a 135 °C oil bath behind a safety shield for 84 h. After being cooled to −78 °C, the tube was opened. A small amount of volatile material boiled away upon warming to room temperature, whereupon the cloudly liquid was transferred to a still equipped with a 10-cm Vigreux column. Distillation at 130 torr gave 5.66 g (70%) of a colorless liquid at 66 °C [lit.[9] bp 119 °C (760 torr)]: $^{19}$F NMR $\delta$ −66.2 (d, $J$ = 20.3, 79%), −68.1 (d, $J$ = 20.3, 21%); partial $^1$H NMR shown in figure 1, complete spectrum included as supplementary material. In a separate experiment three samples at 0.1 this scale were sealed in small tubes and heated at 135 °C for 5, 17, and 40 h. When the tubes were cooled and opened, $^{19}$F NMR analysis showed only the signals observed previously, and in each case the ratio was (80 ± 2):(20 ± 2). Separation of isomers was carried out by preparative gas chromatography at 80 °C. The minor isomer appeared at 5.4 min, and the major isomer appeared at 6.9 min; the minor isomer was collected from 4.7 to 5.7 min, and the major isomer was collected from 6.3 to 7.6 min. Analytical gas chromatography showed each isomer to be >95% pure. Small samples of each isomer were sealed in melting point tubes and heated in a 135 °C oil bath for 22 h. After the samples were cooled, gas chromatographic analysis showed each isomer to be unchanged.

**Registry No. 1a**, 677-21-4; **2a**, 84029-15-2; **3a**, 84029-16-3; cyclopentadiene, 542-92-7.

**Supplementary Material Available:** Figure 2 containing a $^1$H NMR spectrum of a mixture of compounds **2a** and **3a** (1 page). Ordering information is given on any current masthead page.

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[14] Calculations on trifluoromethyl-substituted cations reveal little donation of electron density by the trifluoromethyl group into a vacant $\pi$ orbital. Paddon-Row, M. N.; Santiago, C.; Houk, K. N. *J. Am. Chem. Soc.* **1980**, *102*, 6563.

[15] A comparison with the reaction of propene with cyclopentadiene is of interest since this reaction is reported to give an endo/exo ratio of 3.1:1. It should be noted that the exact numerical value of this ratio is in some doubt and that no effort was made to determine if this represents a kinetic or a thermodynamic ratio. Belikova, N. A.; Berezkin, V. G.; Platé, A. F. *Zh. Obshch. Khim.* **1962**, *32*, 1942.

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# Efficient Synthesis of Methyl 3-Oxo-2,6,6-trimethylcyclohex-1-ene-1-carboxylate, an A-Ring Intermediate for (±)-Strigol

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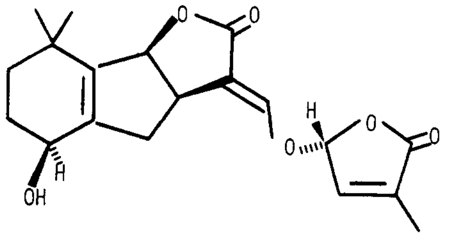
*Received July 20, 1982*

Strigol (**1**) is a highly potent seed germination stimulant for witchweed, a harmful parasitic plant that attacks numerous gramineous crops including corn, sorghum, sugar cane, and rice.[1] Natural strigol is available only in small quantities by tedious isolation from root exudates of cotton, and therefore, efficient chemical synthesis of **1** is prompted. Several partial[2] and two total syntheses[3,4] of (±)-strigol have been reported. The elegant synthesis of **1** by Sih and co-workers has provided gram quantities for biological evaluation. However, there is need to further improve the synthesis to a multigram scale to provide sufficient material for testing strigol as a control agent in witchweed infested fields.



strigol (**1**)

We describe a simple, efficient preparation of methyl 3-oxo-2,6,6-trimethylcyclo-1-ene-1-carboxylate **7** (see Scheme I), a key A-ring intermediate used in the Sih synthesis of **1**. Regioselective epoxidation[5] of commercially available $\alpha$-ionone **2** with *m*-chloroperoxybenzoic acid gave a mixture of isomeric epoxides **3a** and **3b** in 98% yield. Oxidation[6] of the isomeric mixture **3a,b** with sodium metaperiodate and a catalytic amount of potassium permanganate in aqueous 2-methyl-2-propanol resulted in cleavage of the enone functionality to provide the epoxycarboxylic acid **4**. Direct esterification of crude **4** with iodomethane in acetone containing excess potassium carbonate gave epoxy ester **5** in 60% overall yield from **2**. Treatment of **5** with sodium methoxide in methanol resulted in epoxide opening to the allylic alcohol **6** in 96% yield. Oxidation of **6** with pyridinium chlorochromate gave the desired enone **7** in 85% yield.

The synthesis of **7** is accomplished in five steps from readily available and relatively inexpensive $\alpha$-ionone with a 48% overall yield. The synthesis utilizes operationally simple procedures, involves no chromatography, and is

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