JOURNAL OF PHYSICAL ORGANIC CHEMISTRY, VOL. 3, 339–345 (1990)

CYCLOADDITIONS OF 2-DIAZOPROPANE TO BICYCLO[2.2.1]HEPT-2-ENES. DIRECT EXPERIMENTAL EVIDENCE FOR AN ASYNCHRONOUS MECHANISM

MICHAEL W. MAJCHRZAK AND JOHN WARKENTIN*

Department of Chemistry, McMaster University, Hamilton, Ontario, L8S 4M1, Canada

2-Diazopropane, generated by photolysis of 2-methoxy-2,5,5-trimethyl-Δ^3-1,3,4-oxadiazoline, was trapped *in situ* by cycloaddition to norbornene, *endo*- and *exo*-5-methylnorbornene, *endo*- and *exo*-5-phenylnorbornene, *endo*- and *exo*-5-methoxycarbonyl norbornene and *endo*- and *exo*-dicyclopentadiene. In all cases, only *exo* addition was observed. In spite of the *exo* approach of diazopropane to the norbornene double bond, *endo* substituents at C-5 and/or C-6 influenced the regiochemistry of addition whereas *exo* substituents did not. The results are interpreted in terms of a concerted, asynchronous mechanism in which C—C bond formation runs well ahead of N—C bond formation, as predicted from theory. The regiochemical control exercised by apparently remote *endo* substituents provides a new experimental criterion for asynchrony or synchrony of cycloadditions that are known to be concerted.

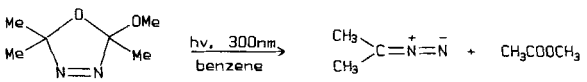
INTRODUCTION

The mechanism of 1,3-dipolar cycloaddition has been investigated thoroughly. Most of the experimental evidence, which is based largely on substituent and solvent effects on rate constants and on stereochemistry points to a concerted, suprafacial mechanism.[1–7] Molecular orbital theory[8–10] describes the concerted mechanism as 'allowed' and predicts, from the appropriate HOMO/LUMO coefficients, which of the newly forming σ-bonds should be strongest at the transition state. Except for cases involving highly symmetric systems, the transition state is expected to have one of the new σ-bonds of the developing five-membered ring stronger than the other.

In this paper we present evidence for such non-synchrony in the cycloaddition reactions of 2-diazopropane to bicyclo[2.2.1]hept-2-enes. The observations point to a potential experimental criterion for synchrony or lack of synchrony of 1,3-dipolar cycloadditions and to a strategy for some control over the regiochemistry of such cycloadditions.

RESULTS AND DISCUSSION

2-Diazopropane (**1**) was generated by the photolysis of 2-methoxy-2,5,5-trimethyl-Δ^3-1,3,4-oxadiazoline (**2**) with 300-nm light in a Rayonet apparatus [equation (1)].[11] The diazopropane was intercepted by the dipolarophile (**3**) also present in the solution of (**2**) [equation (2)]. Those conditions, slow photolysis of **2** and consumption of **1** as it was formed, served to keep the concentration of **1** low and to suppress the formation of acetone azine. Cycloaddition is a thermal process, as indicated by the fact that it becomes very slow when the photolysis is carried out at $-30\,^{\circ}C$. Combined yields of the products **4** and **5** (enantiomers in the case of **4a** and **5a**) were 70% or greater in each case.



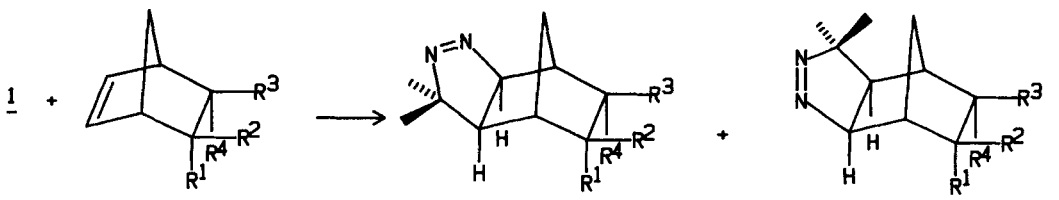
2 **1**

Exo addition to the double bond of the bicyclo[2.2.1]heptene ring was the only mode observed, as expected.[12] The regioisomers (**4b** and **5b**, **4c** and **5c**, etc.) were not readily separable and their structures were therefore assigned by careful analysis of the NMR spectra of the mixtures obtained by separating the isomers from the coproducts but not from each other (see Experimental). The NMR analysis involved the nuclear Overhauser effect (nOe) enhancement[13] technique, $^1H-^{13}C$ shift correlations,[14] Cosy-45[15] and *J*-modulated spin-echo pulse sequences.[16] Those techniques, and unequal populations of the products, led to relatively straightforward assignment of all the ^1H NMR signals of, for example, the isomers **4b** and **5b**.

* Author for correspondence.

0894–3230/90/050339–07$05.00

Received 10 May 1989
Revised 15 August 1989



3 4 5

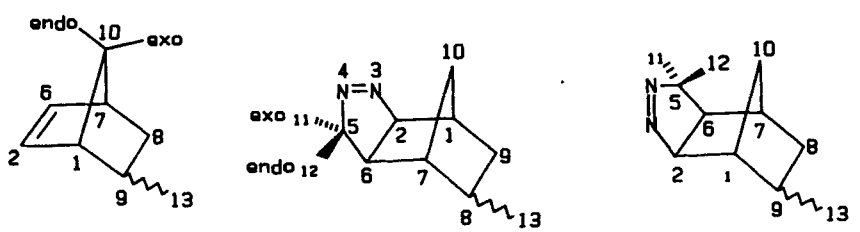
(**a**, $R^1 = R^2 = R^3 = R^4 = H$;
b, $R^1 = CH_3$, $R^2 = R^3 = R^4 = H$;
c, $R^2 = CH_3$, $R^1 = R^3 = R^4 = H$;
d, $R^1 = C_6H_5$, $R^2 = R^3 = R^4 = H$;
e, $R^2 = C_6H_5$, $R^1 = R^3 = R^4 = H$;
f, $R^1R^4 = CH_2CH{=}CH$, $R^2 = R^3 = H$;
g, $R^2R^3 = CH_2CH{=}CH$, $R^1R^4 = H$;
h, $R^1 = CO_2Me$, $R^2 = R^3 = R^4 = H$;
i, $R^2 = CO_2Me$, $R^1 = R^3 = R^4 = H$).

The signals from the *endo*-methyl groups (R^1) were easy to select for nOe experiments. Irradiation of the larger *endo*-methyl doublet at δ 0·80 caused enhancement of the intensity of a doublet at δ 4·74 whereas irradiation of the smaller *endo*-methyl doublet at δ 0·69 did not increase the intensity of either the δ 4·74 doublet or the δ 4·35 doublet significantly. Given that the lower field doublets are those from the N=NCH units, it fol-

Table 1. ^{1}H chemical shifts[a,b,c]

	Compound						
Atom	**3b**	**3c**	**4a**	**4b**	**5b**	**4c**	**5c**
1	2·64	2·38	2·84	2·64	2·58	2·66	2·38
2	5·93	5·99	4·66	4·35	4·74	4·33	4·36
6	6·11	6·08	1·38	1·36	0·96	0·89	0·87
7	2·73	2·77	2·06	1·47	1·62	1·32	1·63
8 *endo*	1·23	1·29	1·09	—	0·75	1·08	1·04
8 *exo*	1·37	1·35	1·46	1·51	0·58	—	0·62
9 *endo*	—	1·45	1·32	0·75	—	1·26	1·35
9 *exo*	2·06	—	1·61	0·58	1·70	0·73	—
10 *exo*	1·86	1·27	0·97	1·56	1·46	0·82	0·82
10 *endo*	0·42	1·03	0·59	0·38	0·23	0·40	0·40
11	—	—	1·43	1·25	1·23	1·22	1·23
12	—	—	1·15	0·97	0·94	0·93	0·92
13	0·77	1·06	—	0·69	0·80	0·67	0·77
Solvent	$CDCl_3$	$CDCl_3$	$CDCl_3$	C_6D_6	C_6D_6	C_6D_6	C_6D_6

[a] Numbering:



3 4 5

[b] For the ^{1}H NMR spectrum of **3a**, see Ref. 17.
[c] Complete assignments of the ^{1}H NMR spectra of **4d** and **5d**, **4e** and **5e**, **4h** and **5h** from spectra of the mixtures containing them was not possible. The relevant signals used to determine isomer ratios in those cases are identified in footnote e in Table 5.

Table 2. ^{13}C chemical shifts[a]

	Compound						
Carbon	**3b**[b]	**3c**[b]	**4a**	**4b**	**5b**	**4c**	**5c**
1	43·24	42·35	37·68	39·18	43·09	38·95	44·85
2	132·98	136·07	97·31	97·85	92·38	97·64	98·32
5	—	—	89·79	89·86	90·23	89·97	89·78
6	137·03	137·13	48·61	40·52	49·26	49·85	48·71
7	47·37	48·34	37·06	42·44	38·80	44·37	38·44
8	33·88	34·61	28·67	33·65	34·70	36·24	39·25
9	32·56	32·59	25·36	34·76	31·98	35·65	33·18
10	50·22	44·85	32·65	34·08	37·67	29·69	29·94
11	—	—	20·12	20·17	20·00	20·56	20·56
12	—	—	28·57	28·75	28·48	29·09	28·89
13	19·44	21·64	—	16·37	17·27	21·86	21·98
Solvent	$CDCl_3$	$CDCl_3$	$CDCl_3$	C_6D_6	C_6D_6	C_6D_6	C_6D_6

[a] Numbering system as in Table 1.
[b] Ref. 17.

lows that the δ 0·80 and 4·74 pair are from **5b** and that the δ 0·69 and 4·35 pair are from **4b**. All of the other signals could then be assigned (Tables 1 and 2) by means of the NMR techniques listed above. Assigments for the mixture obtained from 2-diazopropane and *exo*-methylnorbornene (**4c** and **5c**) were slightly more complicated. Doublets at δ 4·33 and 4·36 could be assigned readily to C-2-H signals of the isomers. The protons closest to H-2 of **4c** and **5c** are those labelled H-1 and H-9 *endo*, and the signals from H-9 *endo* were superimposed on other signals. Nevertheless, it was possible to carry out nOe difference experiments in both senses. Irradiation of the doublet at δ 4·33 increased the intensity of the signals at δ 2·66, 1·26 and 1·08. Similarly, irradiation of the doublet at δ 4·36 increased the intensities of the multiplets at δ 2·38 and 1·35. Confirmation of the chemical shifts of H-9 *endo* were obtained by irradiation at δ 1·26 and 1·35. Those irradiations caused intensity enhancements of the δ 4·33 and 4·36 signals, respectively. Further confirmation of the assignments came from a detailed analysis of the connectivities and coupling constants. Noteworthy features include the fact that the methylene protons (H-8 of **5c** and H-9 of **4c**) are differentiated in that the *exo* proton signal is at higher field than the *endo* proton signal. The signal at δ 0·62 for H-8 *exo* of **5c** is a doublet of triplets (J_{gem} = 12·4 Hz, $J_{8\text{-}exo,9}$ = 4·75 Hz and $J_{8\text{-}exo,7}$ = 4·37 Hz) as is that at δ 0·73 for H-9_{exo} of **4c** (J_{gem} = 12·4 Hz, $J_{9\text{-}exo,1} = J_{9\text{-}exo,8}$ = 4·50 Hz). *Endo* protons, on the other hand, gave rise to partially superimposed quartets of doublets as a result of coupling to neighbors through two large and one small coupling constants. In **5c**, H-8_{endo} has J_{gem} = 12·4 Hz, $J_{8\text{-}endo,9\text{-}endo}$ = 8·52 Hz, and $J_{8\text{-}endo,10\text{-}endo}$ = 2·20 Hz. In **4c** the vicinal coupling is smaller ($J_{9\text{-}endo,8\text{-}endo}$ = 8·37 Hz) and the signal for H-9_{endo} at δ 1·26 is resolved to eight lines.

The origins of couplings were confirmed by applying the decoupling technique. For example, the pseudo doublets at δ 2·66 (H-1 of **4c**) and δ 1·63 (H-7 of **5c**) become sharp singlets on irradiation of the multiplets at δ 0·73 (H-9_{endo} of **4c**) and δ 0·62 (H-8_{endo} of **5c**), respectively. Similarly, the δ 1·26 and δ 1·04 multiplets (H-9_{endo} of **4c** and H-8_{endo} of **5c**, respectively) were simplified to doublets of doublets on irradiation of the δ 0·40 signal (H-10_{endo} of **4c** and **5c**). The chemical shifts of the bridgehead protons (e.g. of **3c**, **4c** and **5c**) illustrate their value as a criterion of structure.

Estimates of the isomer ratio **5c** : **4c**, obtained by integration of the H-1 signals at δ 2·38 and 2·66 and from the intensities of the H-2 signals at δ 4·36 and 4·33, gave 0·88 : 1 and 0·93 : 1, respectively.

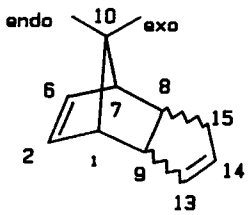
Identification of the isomeric adducts from 2-diazopropane and *endo* dicyclopentadiene, **4f** and **5f**, was also relatively straightforward. Irradiation of the multiplet from the methylene protons of the cyclopentene rings (δ = 2·35) brought about an increase in the intensity of the larger H-2 doublet at δ = 4·72. The major isomer must therefore be **5f**, in which H-2 and one of the allylic protons of the cyclopentene ring are relatively close. Irradiation at δ = 2·11 did not enhance the intensity of the doublet at δ = 4·54. Complete assignments of the ^1H and ^{13}C NMR spectra of **3f**, **3g**, **4f**, **4g**, **5f** and **5g** are given in Tables 3 and 4.

Isomer ratios (**5** : **4**) are collected in Table 5, where the *exo* and *endo* isomers are in separate columns. It is striking that cycloaddition in the *endo* series is regioselective, whereas that in the *exo* series is not. The average isomer ratio (**5** : **4**) in the *endo* series is 1·45, which corresponds to ΔE_a = 237 cal mol^{-1} at 50 °C.

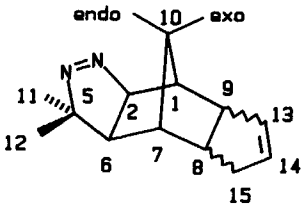
Table 3. ^{1}H chemical shifts of dicyclopentadienes and their adducts with 2-diazopropane[a]

	Compound					
Hydrogen	**3f**	**3g**	**4f**	**5f**	**4g**	**5g**
1	2·86	2·56	2·93	2·11	2·56	2·65
2	5·98	6·07	4·54	4·72	4·75	4·72
6	5·92	6·03	1·38	1·50	1·45	1·49
7	2·77	2·49	1·95	2·76	1·83	1·78
8	2·72	2·22	2·48	3·07	2·57	2·08
9	3·20	2·66	3·17	2·69	2·36	2·78
10 *exo*	1·48	1·47	1·19	1·23	1·16	1·16
10 *endo*	1·29	1·29	0·68	0·73	0·38	0·38
11	—	—	1·38	1·41	1·42	1·42
12	—	—	1·13	1·12	1·15	1·15
13	5·49	5·72	5·68	5·69	5·52	5·40
14	5·46	5·53	5·68	5·45	5·70	5·70
15 *exo*	2·17	2·44	2·11	2·35	2·66	2·55
15 *endo*	1·62	1·86	2·11	2·35	1·99	1·85
Solvent	$CDCl_3$	$CDCl_3$	$CDCl_3$	$CDCl_3$	$CDCl_3$	$CDCl_3$

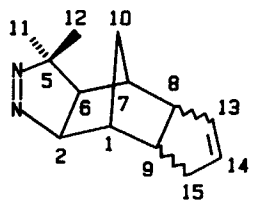
[a] Numbering system:



3



4



5

Table 4. ^{13}C chemical shifts of dicyclopentadienes and their adducts with 2-diazopropane[a]

	Compound					
Carbon	**3f**[b]	**3g**[b]	**4f**	**5f**	**4g**	**5g**
1	45·15	45·58	40·88	39·94	42·34	44·57
2	135·93	137·54	94·65	91·94	97·60	98·09
5	—	—	89·99	90·30	90·10	89·90
6	132·29	137·68	40·47	43·41	49·19	48·85
7	46·17	48·36	41·29	42·12	43·67	41·03
8	54·77	54·42	41·41	53·06	55·53	43·58
9	41·18	42·08	51·18	40·29	52·39	41·03
10	50·29	41·62	35·35	36·06	26·34	26·35
11	—	—	19·88[c]	19·88[c]	20·19	20·19
12	—	—	28·59	28·82	28·70	28·70
13	131·97	133·58	131·65	131·71	137·27	137·51
14	131·91	132·52	131·12	131·30	132·48	133·27
15	34·64	36·85	39·94	31·76	38·74	39·03
Solvent	$CDCl_3$	$CDCl_3$	$CDCl_3$	$CDCl_3$	$CDCl_3$	$CDCl_3$

[a] Numbering system as in Table 3.
[b] Ref. 18.
[c] One negative singlet in the spin-sort spectrum.

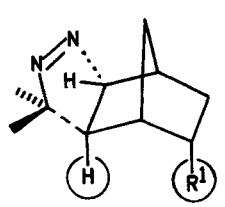
Table 5. Isomer ratios[a]

Substituent	Isomer ratio (4 : 5)[b]	
	Endo[c]	*Exo*
CH_3	1·50, (**5b** : **4b**)	0·93, (**5c** : **4c**)
C_6H_5	1·35, (**5d** : **4d**)[d]	1·00, (**5e** : **4e**)[d]
$CH_2CH=CH$[e]	1·35, (**5f** : **4f**)	1·00, (**5g** : **4g**)
CO_2CH_3	1·61, (**5h** : **4h**)[f]	0·99, (**5i** : **4i**)[f]

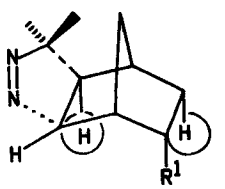
[a] Regioisomers from *exo* addition of 2-diazopropane to a substituted norbornene [equation (2)].
[b] Estimated error ± 0·05.
[c] *Endo* and *exo* designate the position of the substituent in the norbornene substrate.
[d] Ratios determined by integration of the H-2 signals only, in a composite spectrum of all four isomers obtained from a mixture of *exo*- and *endo*-5-phenylnorbornenes. H-2 signals (δ): **4d**, 4·57; **5d**, 4·50; **4e**, 4·48; **5e**, 4·43.
[e] The norbornenes with this 'substituent' are dicyclopentadienes.
[f] H-2 signals (δ): **4h**, 4·71; **5h**, 4·51; **4i**, 4·26; **5i**, 4·25.

The effect is substantial when one considers that, in either case, diazopropane is adding from the *exo* face of norbornene moiety! A direct steric interaction between substituents, *exo* or *endo*, and the approaching dipole cannot be involved.

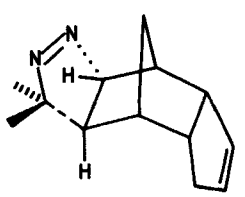
The result can be explained readily in terms of asynchronous cycloaddition, through a transition structure in which the C—C bond is further developed than the N—C bond. A simple illustration, showing partially formed C—C and N—C bonds to model nonsynchronous cycloaddition, is shown in Scheme 1.



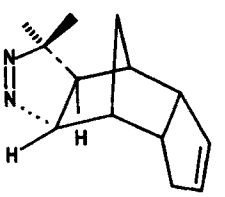
large non-bonded 1,3-interaction



smaller 1,3-interaction



large non-bonded 1,3-interaction



smaller 1,3-interaction

Scheme 1

It is clear from Scheme 1 that extensive rehybridization of the carbon of the dipolarophile that is becoming bonded to carbon of the dipole (where the large HOMO coefficient is located) would place the erstwhile vinyl H into a position that eclipses *endo*-R^1 (1,3-interaction), for one sense of addition, and that eclipses *endo*-H for the other sense of cycloaddition (upper structures, circled atoms or groups). For additions to dicyclopentadiene (lower structures) the two modes of addition differ in that one forces a 1,3-interaction between H and CH_2 whereas the other forces an analogous interaction between H and the planar =CH group. Corresponding differences between developing non-bonded interactions for the two possible modes of addition to the *exo* analogues (not shown in Scheme 1) do not exist. Thus, the picture of the cycloaddition transition state, with C—C bond formation better developed than C—N bond formation, can account, qualitatively, for the observations.

The quantitative aspect presents some difficulty at first because of the evidence that the transistion states for concerted ($\pi 4s + \pi 2s$) cycloadditions come early along the reaction coordinate, particularly for the highly reactive bicyclo[2.2.1]hept-2-ene skeleton.[19] In an early transition state relatively little pyramidalization of either carbon of the 2π component would be expected and therefore the *difference* between the extents of pyramidalization in an unsymmetric early transition state might be expected to be of no consequence, especially if both vinyl substituents moving in the *endo* direction are H atoms. The activation energy difference corresponding to an isomer ratio of 1·45 (0·24 kcal at 50 °C) is indeed small, but it represents about one quarter of the torsional 1,3-interaction between the *endo*-H atom at C-6 and the *endo*-CH_3 group at C-2 of *endo*-5-methylnorbornene. [Calculation by Dr N. H. Werstiuk, using the AMPAC program (Austin Method 1 Package, QCPE 506), Dewar Research Group, and Ref. 20]. The alkene carbons of norbornene are already slightly pyramidalized in the ground state, with the vinyl hydrogens bent out of the C-1—C-2—C-3—C-4 plane,[21] in the *endo* direction, by about 5°. In the transition structure for addition, the degree of pyramidalization of the atom that is attacked can be increased substantially, even if the new bond is weakly formed.[4] Hence it is possible to reconcile the regioselectivity in terms of a cycloaddition transition in which both new σ-bonds are partially developed (early transition state) but in which C—C bond formation is more advanced then N—C bond formation. As a result, the pyramidalization of one olefinic carbon of the norbornene moiety is more advanced than that of the other. Hence the regiochemical preferences for *exo* cycloaddition of **1** to **3** [equation (2)] may be largely the net result of minimization of the new torsional interactions that are developed at the transition states for the two regiochemistries of cycloaddition.

There is an alternative rationale for the results. If a stepwise mechanism[22] with a diradical intermediate is assumed, then the first step would be endothermic and the transition state would resemble that diradical, with the C—C bond largely formed and with N—C bonding not developed at all. One carbon of the norbornene double bond would be rehybridized to essentially sp^3 whereas the other would remain sp^2. Although a stepwise mechanism must be considered,[22] one might expect the selectivities to be larger in that case, reflecting an activation energy difference several times the observed 0·24 kcal mol^{-1}, because the 1,3-non-bonded interactions for the two addition regiochemistries are almost fully developed in the first step of such a stepwise addition. Moreover, there is no evidence yet of non-stereospecific cycloaddition of 1,3-dipoles to alkenes that would require a two-step mechanism.

Two extrapolations from the present results deserve to be highlighted. First, the regioselectivity of *exo* cyclization of other 1,3-dipoles to an *endo*-substituted norbornene might be used as a general probe for inferences about the degree of synchrony of those reactions. Second, a synthetic strategy with some generality might be developed for exerting control over the sense of cycloadditions to cyclic or bicyclic dipolarophiles. It would involve the placing of a bulky steering group judiciously into the dipolarophilic substrate and its subsequent removal after it has exerted its effect.

EXPERIMENTAL

All NMR spectra were recorded on a Bruker AM-500 spectrometer. Proton spectra were acquired at 500·138 MHz using a 5 mm dual frequency $^1H/^{13}C$ probe. A 5·0 μs pulse width (21° flip angle) was used. Spectra were acquired in 8 scans over a 5·0 kHz spectral width in 16K data points (1·638 s acquisition time). A 3·0 s relaxation delay was used. The free induction decay was processed using either exponential or Gaussian multiplication and zero-filled to 32K before Fourier transformation.

Carbon spectra were acquired at 125·759 MHz, using the *J*-modulated spin-echo pulse sequence,[16] in a dual frequency 5 mm $^1H/^{13}C$ probe. The 90° pulse width was 7·3 μs and the relaxation delay was 1·0 s. The free induction decay was processed using exponential multiplication and was zero-filled to 32K before Fourier transformation.

The COSY-45 spectra were obtained in 8 scans for each of the 256 FIDs which contained 1K data points in F_2. Zero-filling in the F_1 dimension during 2D Fourier transformation produced a 512 × 512 data matrix with a digital resolution of 5·17 Hz per point in both dimensions. The 2D data were processed using the squared sine-bell function in both dimensions followed by symmetrization of the transformed matrix.

Proton–carbon connectivity was established using the $^1H-^{13}C$ 2D shift correlation pulse sequence with the addition of the BIRD pulse during the evolution period for ^1H decoupling in the F_1 dimension.[14] The ^1H 90° pulse width through the decoupler channel was 21·2 μs. A relaxation delay of 1·0 s was used. In most cases the data were acquired in 256 scans for each of the 128 FIDs, which contained 4K data points in the F_2 dimension. Zero filling in the F_1 dimension followed by 2D Fourier transformation resulted in a 2048 × 512 data matrix. The data were processed with the application of exponential multiplication in F_2 of the sine-bell function in F_1.

NOE difference spectra were obtained by subtraction of the off-resonance control FID from the on-resonance FID. The signal of interest was selectively saturated for 5·0 s and the decoupler was gated off during acquisition. This saturation period also served as the relaxation delay. Either 8 or 16 scans were acquired for each irradiation with the cycle of irradiations repeated 4–10 times. Free induction decays were processed using exponential multiplication (line broadening 4–5 Hz) before Fourier transformation. Samples were not degassed.

Samples were dissolved either in chloroform-*d* or in benzene-d_6. Chemical shifts are reported in ppm relative to TMS, by using either TMS itself or the residual ^1H resonances of deuterated solvents as internal standard.

The chemical shift for residual ^1H in C_6D_6 was taken to be δ 7·15 and that of ^1H in $CDCl_3$ was taken to be δ 7·20. Corresponding carbon chemical shifts for the two solvents were taken to be δ 128·0 and 77·00, respectively.

Chemicals

Endo- and *exo*-5-norbornene-2-carboxylic acids were separated by the iodolactonization procedure.[23] They were converted to the methyl esters by treatment with thionyl chloride, followed by methanolysis of the acyl chlorides.[24] The *endo-* and *exo*-acids served as the starting materials for *endo-* and *exo*-5-methyl-2-norbornenes, respectively. The latter were prepared readily by reduction of the appropriate acid with lithium aluminium hydride, conversion of the alcohol to the bromide by the reaction of the corresponding tosylate with lithium bromide in acetone,[25] followed by reduction of the bromide by reacting the Grignard reagent with 2% aqueous sulfuric acid. *Exo-* and *endo*-5-phenyl-2-norbornenes were obtained as a 1 : 1 mixture by a published procedure.[26]

Commercial *endo*-dicyclopentadiene was used as received. It was converted to *exo*-dicyclopentadiene by the procedure of Bartlett and Goldstein.[27]

Cycloaddition of 2-diazopropane

2-Diazopropane was generated by photolysis of 2-

methoxy-2,5,5-trimethyl-Δ^3-1,3,4-oxadiazoline with 300 nm light in a Rayonent apparatus.[11] It was trapped *in situ* by the norbornene (**3**) in benzene. Initial concentrations of **3** near 4·0 M were sufficient to suppress azine formation with **3** in 10% excess over **2**. When more than 90% of the **2** had been consumed, the ^{1}H NMR spectrum of the crude sample was taken to establish the product ratio. The sample was then freed from methyl acetate and from remaining **2** and **3** by bulb-to-bulb distallation at 80–100 °C and 0·02 mm Hg in order to permit chemical shift assignments. Distillation did not alter the isomer ratio in any of the samples at the level of detection afforded by ^{1}H NMR spectroscopy.

ACKNOWLEDGEMENTS

We express our thanks to Dr Donald Hughes, McMaster University NMR Facilities, for his assistance with the NMR spectroscopy. Helpful discussions with Professor N. H. Werstiuk, who performed some MNDO calculations, are also gratefully acknowledged.

REFERENCES

1. R. Huisgen, In *Advances in Cycloaddition*, edited by D. P. Curran, Vol. 1, pp. 1–31. JAI Press, Greenwich (1988).
2. R. Huisgen, in *1,3-Dipolar Cycloaddition Chemistry*, edited by A. Padwa, pp. 1–176. Wiley, New York (1984).
3. (a) R. Huisgen and R. Weinberger, *Tetrahedron Lett.* **26**, 5119–5122 (1985); (b) H. Dorn, *Tetrahedron Lett.* **26**, 5123–5126 (1985).
4. K. N. Houk, in *Stereochemistry and Reactivity of Systems Containing π Electrons*, edited by W. H. Watson (*Methods in Stereochemical Analysis*, Vol. 3), pp. 1–40, Verlag Chemie International, Deerfield Beach, FL (1983).
5. R. Huisgen, *Pure Appl. Chem.* **53**, 171–187 (1981).
6. R. Huisgen, *Pure Appl. Chem.* **52**, 2283–2302 (1980).
7. K. N. Houk, *Top. Curr. Chem.* **79**, 1–40 (1979).
8. R. B. Woodward and R. Hoffmann, in *The Conservation of Orbital Symmetry*. Verlag Chemie, Weinheim (1970).
9. K. Fukui, *Acc. Chem. Res.* **4**, 57–64 (1971).
10. I. Fleming, in *Frontier Orbitals and Organic Chemical Reactions*. Wiley, New York (1976).
11. M. W. Majchrzak, M. Békhazi, I Tse-Sheepy and J. Warkentin, *J. Org. Chem.* **54**, 1842–1845 (1989).
12. W. Fliege and R. Huisgen, *Justus Liebigs Ann. Chem.* 2038–2047 (1973).
13. (a) J. K. M Sanders and J. D. Mersh, *Prog. Nucl. Magn. Reson. Spectrosc.* **15**, 353–400 (1982); (b) J. K. M. Sanders and B. K. Hunter, *Modern NMR Spectroscopy*, pp. 163–207. Oxford University Press, New York (1987).
14. (a) A. Bax, *J. Magn. Reson.* **53**, 517–520 (1983); (b) J. A. Wilde and P. H. Bolton, *J. Magn. Reson.* **59**, 343–357 (1984); (c) V. Rutar, *J. Magn. Reson.* **58**, 306–310 (1984).
15. A. Bax and R. Freeman, *J. Magn. Reson.* **44** 542–561 (1981).
16. (a) D. W. Brown, T. T. Nakashima, and D. L. Rabenstein, *J. Magn. Reson.* **45**, 302–314 (1981); (b) C. Le Coco and J. -H. Lallemand, *Chem. Commun.*, 151–152 (1981).
17. J. B. Stothers, C. T. Tan and K. C. Teo, *Can. J. Chem.* **51**, 2893–2901 (1973).
18. (a) E. Fanghänel, Y. Keita, R. Radeglia and W. Schmidt, *J. Prakt. Chem.* **327**, 837–846 (1984); (b) Y. Matoba, T. Kagayama, Y. Ishii and M. Ogawa, *Org. Magn. Reson.* **17**, 144–147 (1981).
19. S. Inagaki, H. Fujimoto and K. Fukui, *J. Am. Chem. Soc.* **98**, 4055–4061 (1976).
20. J. P. Stewart, *ACPE Bull.* **6**, 24 (1986).
21. (a) G. Wipff and K. Morokuma, *Chem. Phys. Lett.* **74**, 400–403 (1980); (b) G. Wipff and K. Morokuma, *Tetrahedron Lett.* **21**, 4445–4448 (1980); (c) N. G. Rondan, M. N. Paddon-Row, P. Caramella and K. N. Houk, *J. Am. Chem. Soc.* **103**, 2436–2438 (1981); (d) P. Caramella, N. G. Rondan, M. N. Paddon-Row and K. N. Houk, *J. Am. Chem. Soc.* **103**, 2438–2440 (1981).
22. R. A. Firestone, *Heterocycles* **25**, 61 (1987).
23. C. D. Ver Nooy and C. S. Rondestvedt, Jr, *J. Am. Chem. Soc.* **77**, 3583–3586 (1955).
24. W. R. Boehme, E. Schipper, W. G. Scharpf and J. Nichols, *J. Am. Chem. Soc.* **80**, 5488–5495 (1958).
25. K. B. Wiberg and B. R. Lowry, *J. Am. Chem. Soc.* **85**, 3188–3193 (1963).
26. K. Alder and M. F. Rickert, **Chem. Ber. 71**, 379–386 (1938).
27. P. D. Bartlett and I. S. Goldstein, *J. Am. Chem. Soc*, 2553 (1947).