C2-H_2), 2.46 (dd, J = 8, 2 Hz, H9), 1.98 (m, C16-H_2), 1.84 (m, H11), 1.72 (dd, J = 12.8, 2 Hz, H10-*endo*), 1.52 (m, H10-*exo*), 1.37 (m, CH_2's), 1.22 (m, CH_2's), 1.16 (m, H15), 0.72 (m, H15); ^{13}C NMR ($CDCl_3$) δ_C 20.9 (C16), 21.4, 25.6 (C15), 28.6, 29.1, 29.8, 35.4 (C2), 39.9 (C10), 45.5, 46.0 (C1, C14), 47.7 (C11), 50.0 (C9), 124.7 (C7), 125.1, 125.2 (C5 and C6), 127.5 (C4), 137.1 (C3), 146.3 (C8). Anal. Calcd for $C_{18}H_{22}$: (M^+) 238.1721. Found: (M^+) 238.1716.

Reactions of 24a, 31, and 35 with Acetic Acid/Sulfuric Acid. The alcohol (2 mmol) was dissolved in glacial acid (30 mL), concentrated sulfuric acid (1 mL) was added, and the mixture was stirred for 20 h. Water (50 mL) was added, and the mixture was extracted with ether (3 × 100 mL). The combined ether extracts were washed until neutral and dried, and the solvent was removed in vacuo to give products that were purified by distillation or chromatography on alumina.

(a) Reaction of 2-*exo*-benzylnorbornanol (24a) at 25 °C gave in 95% yield a 4:1 mixture of the known[40] *E* and *Z* alkenes 2-benzylidenenorbornane (**44** and **45**). **44**: ^1H NMR (CCl_4, 60 MHz) δ_H 7.10 (br s, ArH), 6.17 (t, J = 2.5 Hz, C=C*H*Ar), 3.20 (br s, H1), 2.80 (br s, H4); ^{13}C NMR ($CDCl_3$) δ_C 28.5 (C6), 29.7 (C5), 37.3 (C4), 38.9, 39.1 (C3, C7), 47.8 (C1), 118.0 (C=CHAr), 125.6 (para), 127.7 (ortho), 128.3 (meta), 138.9 (ipso), 149.7 (C2). **45**: ^1H NMR (CCl_4, 60 MHz) δ_H 6.00 (br s, C=C*H*Ph); ^{13}C NMR ($CDCl_3$) δ_C 28.4, 28.8, 35.8, 38.8, 40.4, 41.4, 118.9, 125.7, 127.9, 128.2; bp (for the mixture) 125-135 °C (6 mm). Anal. Calcd for $C_{14}H_{16}$: (M^+) 184.1252. Found: (M^+) 184.1252.

(b) Reaction of 2-*exo*-benzylnorbornanol (24a) at 70 °C gave the above alkenes (50%) and 1-benzylnorbornyl acetate (**46**): ^1H NMR ($CDCl_3$, 60 MHz) δ_H 7.13 (br s, ArH), 4.50 (d, J = 6.5 Hz, H2), 2.83 (s, ArCH_2), 2.06 (s, CH_3); ^{13}C NMR ($CDCl_3$) δ_C 21.3 (CH_3), 29.2, 29.6 (C5, C6), 35.4 (C4), 36.7 (ArCH_2), 39.8 (C7), 41.6 (C3), 51.0 (C1), 78.6 (C2), 125.9 (para), 128.0 (meta), 129.9 (ortho), 139.5 (ipso), 170.5 (C=O).

(c) Reaction of 2-*exo*-benzylcamphenilol (31) as above gave (*E*)-2-benzylidenecamphenilol (**41**) in 85% yield: bp 126-135 °C (10 mm); ^1H NMR ($CDCl_3$, 300 MHz) δ_H 7.00 (m, ArH), 6.01 (s, C=C*H*Ar), 3.27 (d, H1), 1.96 (br s, H4), 1.13 (s, CH_3's); ^{13}C NMR ($CDCl_3$) δ_C 23.8 (C5), 26.3 (*endo*-CH_3), 27.9 (C6), 29.1 (*exo*-CH_3), 38.0 (C7), 42.5 (C1), 43.3 (C4), 116.3 (C=CHAr), 125.5 (para), 128.0, 128.1 (ortho, meta), 139.0 (ipso), 159.2 (C2).

(d) Reaction of 2-*exo*-benzylfenchol (35) as above at 25 °C gave a complex mixture of hydrocarbons, which was not separated but which was shown by ^{13}C NMR to contain alkenes **42** (C=*C*HAr δ_C 116.6) and **43** (δ_C 117.1) as ca. 50% of the mixture.

Acknowledgment. We acknowledge grants from the Research Committee of the New Zealand Universities Grants Committee.

The Triplex Diels-Alder Reaction of 1,3-Dienes with Enol, Alkene, and Acetylenic Dienophiles: Scope and Utility

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The [4 + 2] cycloaddition of an electron-rich diene to an electron-rich dienophile may be catalyzed by irradiation of a cyanoarene. This reaction is shown to proceed through an intermediate ternary excited state complex (triplex) and is therefore called the triplex Diels-Alder reaction. The triplex Diels-Alder reactions of a series of cyclic and acyclic 1,3-dienes with alkenyl benzene, enol ether, and alkynylbenzene dienophiles was investigated. This procedure works extremely well in some cases but poorly in others. A mechanistic hypothesis for the scope and limitations of the triplex Diels-Alder reaction based on these findings is advanced.

Introduction

The Diels-Alder reaction is a convenient, predictable route for the thermal cycloaddition of an electron-deficient dienophile to an electron-rich diene.[1] This reaction often occurs rapidly under mild conditions and has been employed inumerable times for the synthesis of complex materials. In general, however, the Diels-Alder reaction is unsuccessful when both diene and dienophile components are electron-rich compounds. Of the many procedures that have been devised to accelerate the Diels-Alder reaction, none work well for this case. The removal of this restriction seemed imminent in 1981 when Bauld and coworkers discovered that triarylaminium salts initiated the Diels-Alder-like dimerization of 1,3-cyclohexadiene (CHD) and other electron-rich dienes.[2] They proposed a radical cation chain reaction mechanism for this process,[3] and subsequent examinations have supported this path with a few important exceptions.[4,5] However, the aminium salt catalyzed Diels-Alder reaction is often restricted to the dimerization of dienes because of lack of selectivity; the "crossed" cycloadditions that have been reported require very large excesses of the dienophile. Additional complications with this procedure arise when the aminium salt initiates the isomerization or polymerization of the dienophile.[4]

In 1983, Jones and co-workers[6] described a photosensitized dimerization of CHD under conditions where the radical cation chain reaction mechanism is thermodynamically impossible. Our investigation and extension of this discovery led to its generalization as the triplex Diels-Alder reaction.[7] According to this proposal, an exciplex formed

(1) Brieger, G.; Bennet, J. M. *Chem. Rev.* **1980**, *80*, 63.
(2) Bellville, D. J.; Wirth, D. D.; Bauld, N. L. *J. Am. Chem. Soc.* **1981**, *103*, 718.
(3) Schenck, G. O.; Mannsfeld, S.-P.; Schombert, G.; Krauch, C. H. *Z. Naturforsch.* **1964**, *19B*, 18. Schutte, R.; Freemen, G. R. *J. Am. Chem. Soc.* **1969**, *91*, 3715. Penner, T. L.; Whitten, D. G.; Hammond, G. S. *J. Am. Chem. Soc.* **1970**, *92*, 2861.
(4) Bellville, D. J.; Bauld, N. L. *J. Am. Chem. Soc.* **1982**, *104*, 2665. Pabon, R. A.; Bellville, D. J.; Bauld, N. L. *J. Am. Chem. Soc.* **1983**, *105*, 5158. Pabon, R. A.; Bellville, D. J.; Bauld, N. L. *J. Am. Chem. Soc.* **1984**, *106*, 2730. Reynolds, D. W.; Lorenz, K. T.; Chiou, H.-S.; Belleville, D. J.; Pabon, R. A.; Bauld, N. L. *J. Am. Chem. Soc.* **1987**, *109*, 4960. Mattay, J. *Nachr. Chem. Tech. Lab* **1988**, *36*, 376. Mlcoch, J.; Steckhan, M. *Angew. Chem. Int. Ed.* **1985**, *24*, 412.
(5) Gassman, P. G.; Singleton, D. A. *J. Am. Chem. Soc.* **1984**, *106*, 6085. Gassman, P. G.; Singleton, D. A. *J. Am. Chem. Soc.* **1984**, *106*, 7993.
(6) Jones, C. R.; Allman, B. J.; Mooring, A.; Spahic, B. *J. Am. Chem. Soc.* **1983**, *105*, 652.

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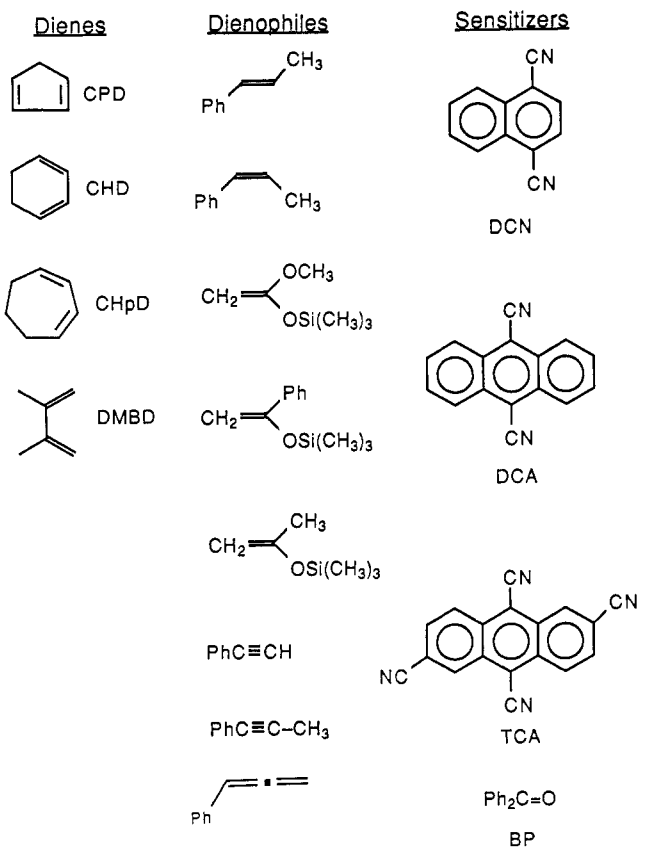
Chart I



from the excited singlet state of an electron-deficient arene (the sensitizer, a catalyst) and the dienophile is trapped by the diene to form a ternary excited state complex (triplex) which, as an intermediate or transition state, proceeds to give Diels–Alder-like cycloadducts. In a previous report we described application of the triplex Diels–Alder reaction in the addition of CHD to indene.[7] Herein we report results of the investigation of the scope and mechanism of the triplex Diels–Alder reaction of some cyclic and acyclic dienes with electron rich dienophiles selected from among silyl enol ethers, alkenes, and acetylenes (Chart I).[8]

Results

(A) The Sensitizers. The function of a sensitizer in a photochemical reaction is to absorb the actinic light and, while in its light-activated state, by some means initiate a chemical reaction. Two kinds of sensitizers were employed in this work. The first group is cyano-substituted arenes: 1,4-dicyanonaphthalene (DCN), 9,10-dicyanoanthracene (DCA), and 2,6,9,10-tertracyanoanthracene (TCA).[9] They are each specially effective sensitizers of the triplex Diels–Alder reaction under some conditions. For contrast in some mechanistic studies, we employed the classical triplet sensitizers benzophenone (BP) or 3-isopropylthioxanthone (ITX).

(B) Quenching of the Sensitizer and Exciplex Formation. Both the dienophiles and the dienes used in this study are usually effective quenchers of the cyanoarene

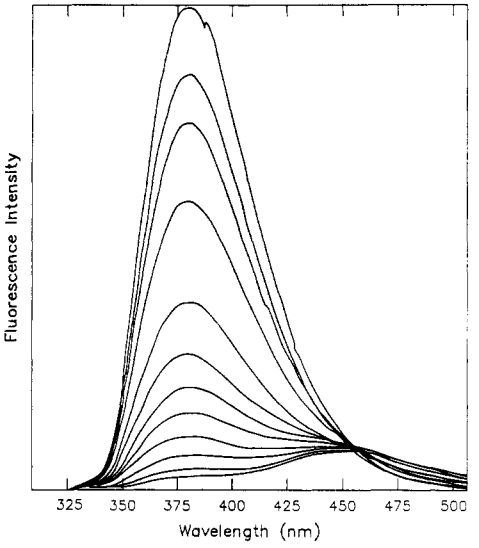


Figure 1. The fluorescence of DCN in benzene solutions containing increasing amounts of *trans*-β-methylstyrene.

excited singlet states. The rate constants for the quenching were determined by conventional Stern–Volmer techniques, and the expected trend is readily apparent. The lower the oxidation potential of the quencher, the more rapidly it reacts with the cyanoarene.

Calculations from the Weller equation[10] indicate that electron transfer to form the radical anion of the sensitizer and the radical cation of the dienophile quencher should be rapid for many of the cases studied in a polar solvent such as CH_3CN but thermodynamically impossible in a nonpolar solvent like benzene or dioxane. This prediction was confirmed by laser transient absorption spectroscopy. For example, irradiation of DCN (337 nm, 7 mJ, 13 ns) in CH_3CN containing *trans*-β-methylstyrene (0.13 M) clearly reveals the rapid formation of $DCN^{\bullet-}$.[11] When this experiment is repeated with benzene or dioxane as the solvent, the spectrum of $DCN^{\bullet-}$ cannot be detected.

The quenching of the cyanoarene sensitizer by the dienophile in benzene or dioxane proceeds through an exciplex. In some cases the exciplex can be detected by its characteristic emission. Figure 1 shows the fluorescence of DCN in benzene solutions containing increasing concentrations of *trans*-β-methylstyrene. The broad structureless emission with a maximum at 450 nm is assigned to the DCN–styrene exciplex. Similarly, the emission of the 1-phenylpropyne–DCN exciplex in *p*-dioxane solution occurs at 420 nm.

Significantly, the exciplex formed from the cyanoarene and the dienophile, in some cases, can be shown conclusively to react with the diene. For example, in benzene solution the lifetime of the DCN–*trans*-β-methylstyrene exciplex is reduced as the concentration of CHD is increased. Conventional kinetic analysis of these data gives a value for the bimolecular rate constant for formation of the DCN–styrene–CHD triplex of 9.1×10^8 M^{-1} s^{-1}. For the phenylpropyne–DCN exciplex this quenching rate constant in dioxane solution is 3.5×10^9 M^{-1} s^{-1}, nearly the diffusion limited value. These observations confirm triplex formation but do not insure that this intermediate is on the reaction path leading to Diels–Alder-like adducts.

(C) Triplex Diels–Alder Reaction of CHD and *trans*- or *cis*-β-Methylstyrene. Irradiation (450-W Hg lamp, Pyrex or uranium glass filter) of a TCA-saturated

(7) Calhoun, G. C.; Schuster, G. B. *J. Am. Chem. Soc.* **1984**, *106*, 6870. Calhoun, G. C.; Schuster, G. B. *Tetrahedron Lett.* **1986**, *27*, 911. Calhoun, G. C.; Schuster, G. B. *J. Am. Chem. Soc.* **1986**, *108*, 8021.

(8) Some of these results have been communicated in preliminary reports. Akbulut, N.; Schuster, G. B. *Tetrahedron Lett.*, in press. Hartsough, D.; Schuster, G. B. *J. Org. Chem.*, submitted for publication.

(9) Mattes, S. L.; Farid, S. *J. Am. Chem. Soc.* **1983**, *105*, 1386.

(10) Rehm, D.; Weller, *Isr. J. Chem.* **1970**, *8*, 259.

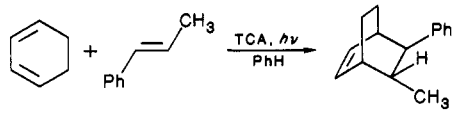
(11) Peacock, N. J.; Schuster, G. B. *J. Am. Chem. Soc.* **1983**, *105*, 3632.

Table I. Relative Yields of Cycloadducts from Reactions of CHD and β-Methylstyrenes

				endo		exo			
styrene, M	CHD, M	sens	solvent	*trans*-1a	*cis*-1b	*trans*-2a	*cis*-2b	$[CHD]_2$	[2 + 2]
trans, 0.13	0.13	TCA	dioxane	82	ND[a]	3	ND	9	6
cis, 0.13	0.13	TCA	dioxane	Tr[b]	61	ND	13	16	10
trans, 0.13	0.13	DCN	dioxane	11	ND	tr	ND	83	5
cis, 0.13	0.13	DCN	dioxane	tr	8	ND	2	85	4
trans, 0.76	0.26	DCN	CH_3CN	3	ND	tr	ND	97	tr
cis, 0.76	0.26	DCN	CH_3CN	ND	tr	ND	tr	99	tr
trans, 0.13	0.25	$(Ar)_3N^+$	CH_2Cl_2[c]	2	ND	tr	ND	98	tr
cis, 0.10	0.23	$(Ar)_3N^+$	CH_2Cl_2	ND	ND	ND	ND	100	ND
trans, 0.76	0.26	Ph_2CO	C_6H_6	ND	ND	tr	ND	93	7
cis, 0.76	0.26	Ph_2CO	C_6H_6	tr	ND	tr	ND	90	10
trans, 3.1	9.8	thermal	none[d]	2	ND	3	ND	95	ND
cis, 3.1	9.8	thermal	none[d]	ND	2	ND	tr	98	ND

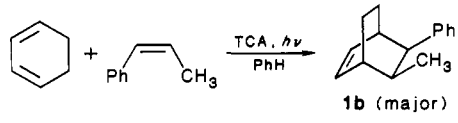
[a] ND: No peak is detected by capillary GC with the retention time corresponding to this product. [b] Tr: A small peak in the capillary GC trace with the proper retention time is observed, but it represents less than 1% of the product mixture. [c] This experiment was run under the radical cation Diels–Alder conditions described by Bauld and co-workers[4] but modified to contain 0.03 M 2,6-di-*tert*-butyl-4-methylpyridine as recommended by Gassman and co-workers.[5] [d] The experiment was run with degassed, sealed tubes of the reactants kept at 180 °C for 40 h.

dioxane solution of *trans*-β-methylstyrene and CHD (0.13 M each) gives one major product and several minor products. The major product is the endo-trans adduct **1a**, the exo-trans isomer **2a** is one of the very minor products, and neither of the cis adducts could be detected by gas chromatography (<1%) (eq 1). Photolysis of a similar solution containing *cis*-β-methylstyrene (0.13 M) gives primarily endo-*cis* adduct **1b**; only trace amounts of the trans adducts **1a** and **2a** could be detected (eq 2). Under



(1)

1a (major)



(2)

1b (major)

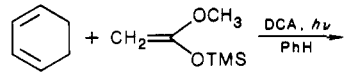
these photolysis conditions, the only significant side reactions are dimerization of the CHD[12] and addition of CHD to the styrenes to form bicyclo[4.2.0]octenes {[2 + 2]adducts} in yields of ca. 12 and 5%, respectively, and the TCA is slowly consumed.

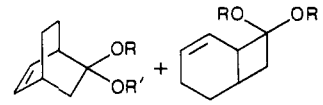
It is clear from these findings that the triplex Diels–Alder procedure provides a practical, convenient, stereospecific route for the formation of substituted bicyclo[2.2.2]octenes. This reaction may be carried out on a preparatively useful scale. TCA-sensitized photolysis of a dioxane solution of either the *trans*- or *cis*-β-methylstyrene and CHD gives the endo-trans or cis Diels–Alder-like adducts in 75% (trans) or 50% (cis) yield at 50% conversion of the styrene. These adducts can be isolated simply by distillation of the crude photolysis mixture.

In contrast to the results of the triplex-initiated reaction, our attempts to add the methylstyrenes to CHD by the radical cation Diels–Alder cycloaddition procedure, initiated either by the aryl aminium salt or by irradiation of 1,4-dicyanonaphthalene (DCN) in acetonitrile solution, did not give meaningful yields of the desired cycloadducts. Instead, overwhelming amounts of CHD dimers are formed in this procedure. Similarly, the conventional thermal Diels–Alder procedures failed to give useful yields of the adducts of CHD to the methylstyrenes, and irradiation with usual triplet sensitizers (BP in benzene solution) gives predominantly the dimers of CHD. The only practical one-step procedure for the cycloaddition of CHD to the methylstyrenes is the triplex Diels–Alder route. These results are summarized in Table I.

(D) Triplex Diels–Alder Reaction with Silyl Enol Ether Dienophiles. The [4 + 2] cycloaddition of an enolic dienophile to a simple diene, potentially a very useful reaction, cannot be accomplished by conventional means. We studied the utility of the triplex Diels–Alder approach for this process by examination of a group of cyclic and acyclic dienes with silyl enol ethers and silyl ketene acetals as dienophiles.

Irradiation of a benzene solution of DCA containing CHD and 1-(trimethylsiloxy)-1-methoxyethene gives three groups of products. The first group is the dimers of cyclohexadiene, the second group is dimers of the ketene acetal, and the third group contains four isomeric compounds that are all 1:1 adducts of CHD and the ketene acetal. Acid-catalyzed hydrolysis of the crossed adducts gives two isomeric ketones in a ratio of 1:3. The minor ketone was identified as bicyclo[2.2.2]oct-5-en-2-one by comparison with an authentic sample. The major ketone product is bicyclo[4.2.0]oct-2-en-8-one; its structure was confirmed by catalytic hydrogenation to bicyclo[4.2.0]octan-2-one followed by comparison with an independently prepared sample. Consideration of these findings leads to assignment of the four photoadducts as endo and exo [2 + 2] and [4 + 2] cycloaddition products (eq 3). These and other findings for the enolic dienophiles are summarized in Table II.



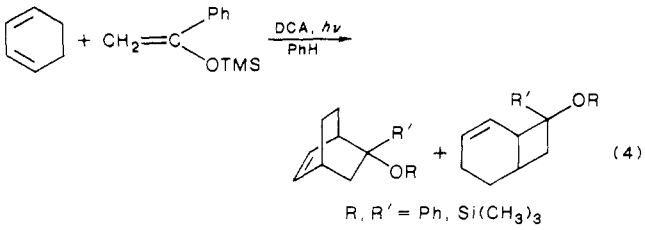


(3)

R, R' = CH_3, $Si(CH_3)_3$

The DCA-sensitized cycloaddition reaction of CHD in benzene also proceeds when silyl enol ethers are the dienophiles. Irradiation of a benzene solution of 1-(trimethylsiloxy)-1-phenylethene containing CHD and DCA gives the CHD dimers four isomeric adducts of CHD to the enol ether (eq 4). One pair of adducts was identified as the endo and exo isomers of 2-phenyl-2-(trimethylsiloxy)bicyclo[2.2.2]oct-5-ene, the Diels–Alder-like [4 + 2] cycloaddition products: catalytic hydrogenation of the mixture of the two isomeric [4 + 2] adducts converts both

(12) Valentine, D.; Turro, N. J.; Hammond, G. S. *J. Am. Chem. Soc.* **1964**, *86*, 5202.



(4)

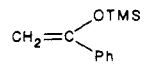
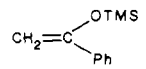
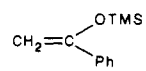
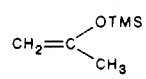
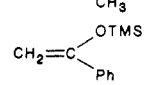
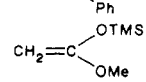
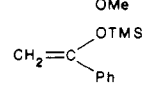
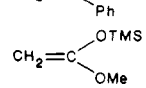
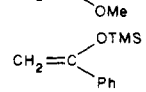
to a single compound, 2-phenyl-2-(trimethylsiloxy)bicyclo[2.2.2]octane, which was identified by comparison with an authentic compound prepared independently. The endo phenyl isomer was distinguished from the exo isomer by analysis of their ^{1}H NMR spectra. The endo isomer exhibits a characteristic splitting and upfield shift of the vinyl hydrogens in the etheno bridge that is absent in the exo isomer. The other two adducts formed in the DCA-sensitized reaction are the endo and exo isomers of 8-phenyl-8-(trimethylsiloxy)bicyclo[4.2.0]oct-2-ene, the [2 + 2] cycloaddition products. These compounds were prepared independently by BP-sensitized addition of the enol ether to the diene. In this case, the endo and exo isomers were distinguished by the upfield shift and splitting of the vinyl hydrogens in the ^{1}H NMR spectrum of the former. The [4 + 2] and [2 + 2] cycloadducts in the DCA-sensitized reaction of CHD and 1-(trimethylsiloxy)-1-phenylethene are formed in 80% yield (35% conversion in a 3.5:1 ratio. The proportion of exo to endo isomers for both the [2 + 2] and [4 + 2] cycloaddition products is nearly equal. When DCN is used as the sensitizer, triplet reactions play a more important role, and the yield of the [4 + 2] adducts decreases relative to the [2 + 2] product. When benzophenone is the sensitizer, only a trace of the [4 + 2] cycloadducts can be detected.

Significantly, the triplex Diels–Alder reaction of silyl enol ethers does not require an aryl substituent. DCA-sensitized irradiation of a benzene solution of 2-(trimethylsiloxy)propene and CHD leads to a mixture of CHD dimers, exo and endo [4 + 2] cycloadducts, and exo and endo [2 + 2] cycloadducts. The cycloadducts were identified by comparison with authentic compounds prepared independently. These results are summarized in Table II.

The DCA-sensitized reactions of 1,3-cyclopentadiene (CPD) with the enolic dienophiles are similar to those observed when CHD is the diene. With 1-(trimethylsiloxy)-1-phenylethene as the dienophile, the reaction yields CPD dimers along with endo and exo [4 + 2] and [2 + 2] cycloadducts of the enol to the CPD. The ratio of [4 + 2] to [2 + 2] adducts formed was determined to be 80:1 by acid-catalyzed dehydration of the crude mixture of adducts and then comparison of these products with authentic 2-phenylbicyclo[2.2.1]hepta-2,5-diene. As with CHD, the ratio of endo to exo isomers is nearly unity. When 1-(trimethylsiloxy)-1-methoxyethene was used as the dienophile in the reaction with CPD, the cycloadducts were hydrolyzed to their respective ketones, and these were identified by comparison with authentic samples. The ratio of bicyclo[2.2.1]hept-2-en-5-one, the [4 + 2] adduct, to bicyclo[3.2.0]hept-3-en-6-one, the [2 + 2] adduct, is 1:2. These findings are also summarized in Table II.

In contrast to the findings for CHD and CPD, when cycloheptadiene (CHpD) and the silyl enol ethers are subjected to the triplex procedure in benzene solution with DCA, the cycloadducts obtained result almost exclusively from the [2 + 2] cycloaddition mode. Similarly, [2 + 2] cycloadducts are formed almost exclusively when 2,3-dimethyl-1,3-butadiene (DMBD) or 1,3-butadiene (BD) is the dienophile component in the DCA-sensitized triplex Diels–Alder reaction of these enols.

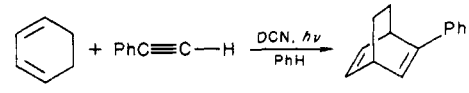
Table II. Triplex Diels–Alder Reaction with Enolic Dienophiles: Relative Product Yields

dienophile	diene	sens	[4 + 2]	[2 + 2]
	CHD	DCA	3.5	1.0
	CHD	DCN	1.0	3.7
	CHD	BP	1.0	43
	CHD	DCA	3.5	17
	CPD	DCA	80[a]	1.0
	CPD	DCA	1.0[b]	2.0
	CHpD	DCA	minor	major[c]
	CHpD	DCA	2.0[b]	1.0
	DThBD	DCA	trace	major[d]

[a] Product ratio determined after dehydration to 2-phenylbicyclo[2.2.1]hepto(-2,5-diene). [b] Product ratio determined after hydrolysis to the ketones. [c] The synthesis of authentic adducts gives only one stereoisomer of the [4 + 2] adduct. The triplex procedure gives both. [d] The [4 + 2] adducts are less than 1% of the mixture.

(E) Triplex Diels–Alder Reaction with Acetylenic Dienophiles. Acetylenic compounds are usually reluctant dienophiles, and Diels–Alder reaction involving acetylenes are very difficult to accomplish in the absence of a strongly activating substituent. Farid and co-workers reported photosensitized dimerization of phenylacetylene sensitized by TCA in acetonitrile solution,[13] but little else was known about photoinitiated cycloaddition reactions involving acetylenes as dienophiles.

Irradiation of a benzene solution containing DCN or TCA with CHD and phenylacetylene leads to the formation of two kinds of products: dimers of CHD and a 4% yield (at 35% conversion) of a 1:1 adduct of CHD and phenylacetylene (eq 5). The adduct of CHD to phenyl-



(5)

acetylene was shown to be 2-phenylbicyclo[2.2.2]octa-2,5-diene by comparison with an independently prepared sample. The yield of the [4 + 2] cycloadduct relative to the CHD dimers increases with increasing concentration of the acetylene in the reaction mixture. When the reaction of CHD and phenylacetylene is sensitized by ITX, a 25% yield (at 14% conversion) of the octadiene cycloadduct is obtained.

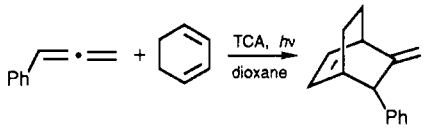
The DCN-sensitized irradiation of CHD and phenylpropyne in dioxane solution gives results similar to those obtained when phenylacetylene is the dienophile. Two types of products are formed: CHD dimers and a 30% yield (at 10% conversion) of the [4 + 2] adduct identified spectroscopically as 2-methyl-3-phenylbicyclo[2.2.2]octa-2,5-diene. When a DCN-containing solution of CHD (0.2 M) in phenylpropyne is irradiated for 2 h, the [4 + 2]

(13) Farid, S.; Mattes, S. L. *J. Chem. Soc., Chem. Commun.* **1980**, 126.

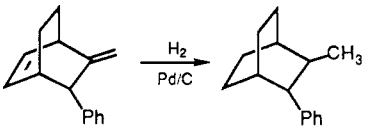
bicyclic adduct to CHD dimer ratio is 8:1.

TCA-sensitized irradiation of a dioxane solution of DMBD and phenylacetylene leads to one product identified as the [2 + 2] cycloadduct by spectroscopic means. Similarly, TCA-sensitized irradiation of a benzene solution of DMBD and phenylpropyne gives only the [2 + 2] cycloadduct (81% at 25% conversion). Irradiation of ITX with DMBD and phenylpropyne under similar condition gives no cycloadduct. These findings extend the trend observed with the enolic dienophiles; acyclic dienes tend to give predominantly [2 + 2] cycloadducts under the triplex conditions.

(F) Triplex Diels–Alder Reaction with Allenyic Dienophiles. Phenylallene was investigated for suitability as the dienophile component of the triplex Diels–Alder reaction. Irradiation of a dioxane solution of TCA containing phenylallene and 1,3-cyclohexadiene results in the formation of two groups of products. The first group is composed of the dimers of CHD. The second group of products is made up primarily of the [4 + 2] adducts of CHD and phenylallene (eq 6). Hydrogenation of the reaction mixture enables identification of the [4 + 2] cycloadducts by comparison with authentic materials (eq 7). The triplex reaction gives reduced [4 + 2] adducts in an overall yield of 30% for the two steps, based on 50% conversion of the phenylallene.



(6)



(7)

Discussion

The primary objective of this work was to explore the scope and utility of the triplex Diels–Alder reaction for crossed intermolecular cycloaddition of an electron-rich diene to an electron-rich dienophile. The major issues associated with this objective are: the range of diene and dienophile structures that will undergo the triplex reaction; retention or loss of stereochemistry of the dienophile component; factors influencing the selection of the [2 + 2] or [4 + 2] modes of cycloaddition; and the potential for practical application of the triplex methodology. As part of our study of these questions, we obtained additional information about the details of the mechanism for this reaction.

(A) Range of Diene and Dienophile Structures. Previous work on the triplex Diels–Alder reaction was limited to examination of the dimerization of CHD and the addition of CHD to aryl-substituted alkenes.[7] Those findings have been extended in this work. The range of dienophiles that will add to CHD has been shown to include enol ethers, ketene acetals, and aryl-substituted acetylenes. However, the reactions of these dienophiles are sometimes unsuccessful. First, in all cases, the desired crossed cycloaddition reaction competes with the dimerization of the diene. This is not a serious difficulty when the diene is readily available and its dimers easily removed from the product, but this reaction clearly represents a limitation to the general utility of the triplex procedure.

In each case examined, the enolic and alkenyl benzene dienophiles give mixtures of [2 + 2] and [4 + 2] cycloaddition products. For the enol ethers and alkenes the [4 + 2] mode dominates, but for the ketene acetal the [2 + 2] mode is favored. This observation may illuminate some details of the reaction mechanism, but the lack of specificity represents a second drawback of the triplex method.

Scheme I

$$\text{sens}^{*1} + \text{dienophile} \longrightarrow \underset{\text{exciplex}}{(\text{sens}\cdots\text{dienophile})^{*1}}$$

$$(\text{sens}\cdots\text{dienophile})^{*1} + \text{diene} \longrightarrow \underset{\text{triplex}}{(\text{sens}\cdots\text{dienophile}\cdots\text{diene})^{*1}}$$

$$(\text{sens}\cdots\text{dienophile}\cdots\text{diene})^{*1} \longrightarrow [4+2] \text{ and } [2+2] \text{ adducts}$$

$$(\text{sens}\cdots\text{dienophile})^{*1} \longrightarrow \text{sens}^{*3} + \text{dienophile}$$

$$\text{sens}^{*3} + \underset{\text{dienophile}}{\overset{\text{diene}}{\text{or}}} \longrightarrow \text{dimers and } [2+2] \text{ adducts}$$

A third limitation concerns the efficiency of the triplex reaction with acetylenic dienophiles. These reactions evidently have low quantum efficiencies relative to even inefficient paths that result in irreversible consumption of the acetylene. This will be a serious problem when the acetylene is not readily available or easily separated from the product.

Our examination also turned up some limitations to the structure of the diene for the triplex Diels–Alder reaction of enolic and acetylenic dienophiles. For the enol ethers, the ratio of [4 + 2] to [2 + 2] cycloaddition mode decreases with the series CPD, CHD CHpD, DMBD. For CPD the [4 + 2] mode is dominant, but for the acyclic diene, only a trace of the [4 + 2] cycloaddition product can be detected. The same general trend is observed with acetylenic dienophiles. This shift in the addition mode is associated tentatively with a more flexible diene yielding a greater fraction of [2 + 2] cycloadduct.

(B) Stereochemical Examination of the Triplex Diels–Alder Reaction. Two issues have been examined with regard to the stereochemistry of the triplex Diels–Alder reaction. With the alkenylbenzene dienophiles, the triplex process gives primarily endo adducts with essentially complete retention of dienophile configuration. This result has significance both for the synthetic applications of this method and for the further understanding of its mechanism. The degree of endo selection may be the consequence of a competition between secondary-orbital overlap[14] and steric crowding in the transition structure, particularly in the triplex where additional rigidity beyond that of the normal Diels–Alder transition state is presumed because of "back side" contact between the dienophile and the sensitizer. The highly stereospecific reactions observed with the β-methylstyrene dienophiles provides convincing evidence that the reaction sequence does not proceed through a "one-bond" intermediate where rotation to another conformation is faster than the formation of the second bond.

When the enolic dienophiles are used in the triplex procedure both endo and exo [4 + 2] cycloadducts are formed in nearly equal amounts. This observation represents a limit to the practical utility of the triplex procedure and suggests that the transition structure for these dienophiles is more "open" than for the alkenes. This may be a consequence of the increased ability of the enols to stabilize a positive charge in the transition structure.

(C) Mechanism of the Triplex Diels–Alder Reaction. The proposed mechanism for the triplex Diels–Alder reaction is outlined in Scheme I. The photophysical results require the formation of a ternary complex with the

(14) Hoffmann, R.; Woodward, R. B. *J. Am. Chem. Soc.* **1965**, *87*, 4388.

structure sens···dienophile···diene. However, they do not require this complex to be on the path that ultimately gives the cycloadducts. Additional support for the participation of this particular triplex comes from the product studies. Cycloadducts are formed only in those cases where the dienophile is a good quencher of the singlet excited sensitizer. This finding does not define the order of the components in the triplex, but it is at least supportive of the structure shown which is consistent with previous conclusions about the structure of triplexes.[15]

Conclusions

The triplex Diels–Alder reaction provides a useful one-step procedure for the formation of cycloadducts between certain cyclic electron-rich dienes and certain electron-rich dienophiles. However, there are serious limitations to the triplex procedure in some cases. These limitations are related to competing reactions of the diene and the dienophile and to the absence of cycloaddition mode specificity in many cases. With these limitations in mind, it seems that the real potential of the triplex Diels–Alder reaction may lie in its application to intramolecular cycloaddition reactions. In these cases the competing reactions of the diene and dienophile will be much less important, and the mode-selectivity issue will usually be determined by exogenous ring-strain considerations. A test of the utility of the triplex procedure for intramolecular examples is under way in our laboratory.

Experimental Section

General Procedures. Benzene was shaken with cold concentrated H_2SO_4 until the acid layer was not discolored and then it was distilled from sodium. *p*-Dioxane was distilled first from $NaBH_4$ and then from sodium. TCA and DCN were prepared by standard procedures,[9] DCA was purchased from Kodak. Tris(*p*-bromophenyl)aminium hexachlorostibnate was purchased from Aldrich and purified by precipitation from CH_2Cl_2 by addition of diethyl ether. 2,3-Dimethyl-1,3-butadiene, isoprene, and 1,3-butadiene were used as received. Phenylacetylene was distilled fractionally under vacuum. The enol ethers and ketene acetals were prepared and purified by standard procedures.[16] ^1H NMR and ^{13}C NMR spectra were recorded with either a Varian XL-200 spectrometer or a General Electric QE-300 spectrometer. ^1H NMR spectra were referenced to tetramethylsilane, and ^{13}C NMR spectra were referenced to $CDCl_3$. Analyses using gas chromatography were performed with a Varian 3700 chromatograph using an HP-5 capillary column or with a Hewlett-Packard 5890A using an OV-17 megabore column. GC/MS analyses were done with a Hewlett-Packard 5890A gas chromatograph with a Hewlett-Packard 5970 mass selective detector. Hexadecane was used as an internal standard for yield calculations. Product identification was made by co-injection with authentic compounds and by GC/MS. Fluorescence spectra were recorded with a Farrand Mark I spectrofluorometer. Emission lifetimes were recorded on the Lifetime 2 instrument of the Laboratory for Fluorescence Dynamics at the University of Illinois.

Photolyses. Typically, solutions of the diene, dienophile, and sensitizer at appropriate concentrations were prepared in a stir-bar-equipped Pyrex tube. TCA and DCA solutions were saturated in the sensitizer. When run under O_2-free conditions, the solutions were purged with N_2 for 3 min and photolyzed under a positive N_2 pressure; there appears to be no significant effect of O_2 on these reactions, however. Irradiation of samples at 350 nm (DCA, DCN, or BP sensitization) was carried out in a Rayonet photoreactor with 350-nm lamps. TCA-sensitized photolyses were irradiated with a 450-W Hg lamp equipped with a uranium glass filter.

Preparation of Authentic *endo*- and *exo*-*trans*-5-Methyl-6-phenylbicyclo[2.2.2]oct-2-ene. The Diels–Alder reaction of *trans*-cinnamaldehyde and CHD was carried out as previously described.[17] The endo and exo bicyclic aldehydes were separated on silica gel with 8% EtOAc–hexane. ***exo*-Phenyl**: GC/MS *m/e* (rel abundance) 212 (1), 134 (35), 133 (50), 115 (10), 80 (100), 79 (44), 77 (19); ^1H NMR δ 1.22–1.38 (m, 2 H), 1.45–1.54 (m, 1 H), 2.56–2.59 (m, 1 H), 2.74–2.76 (m, 1 H), 3.09–3.12 (m, 1 H), 3.39–3.41 (m, 1 H), 6.39 (dd, 1 H, $J_1 = J_2 = 7.2$), 6.49 (dd, 1 H, $J_1 = J_2 = 7.2$), 7.14–7.27 (m, 5 H), 9.8 (s, 1 H). ***endo*-Phenyl**: GC/MS *m/e* (rel abundance) 212 (6), 134 (32), 133 (50), 115 (11), 80 (100), 79 (46); ^1H NMR δ 1.03–1.12 (m, 1 H), 1.43–1.52 (m, 1 H), 1.66–1.77 (m, 2 H), 2.62–2.64 (m, 1 H), 2.83–2.85 (m, 1 H), 3.08–3.10 (m, 1 H), 3.20–3.22 (m, 1 H), 6.20 (dd, 1 H, $J_1 = J_2 = 7.2$), 6.53 (dd, 1 H, $J_1 = J_2 = 7.2$), 7.21–7.37 (m, 5 H), 9.55 (d, 1 H, $J = 0.9$).

The bicyclic aldehydes were reduced under Wolff–Kischner[18] conditions to the hydrocarbons. The endo aldehyde (0.51 g, 2.4 mmol) was added to 15 mL of diethylene glycol and 5 mL of ethyl alcohol containing 0.4 mL of a 55% aqueous solution of hydrazine hydrate. The solution was heated at reflux for 30 min, and then a solution of KOH (0.54 g in 3 mL of H_2O) was added and the solution heated an additional 40 min. Unreacted starting aldehyde was removed by steam distillation, and residue was heated at 200 °C for 1.5 h. The crude product was added to 15 mL of H_2O and separated by extraction with ether. The ether layer was dried, and the solvent was removed to yield 338 mg of a pale yellow oil. Purification of the crude product by filtration through silica gel with pentane gave 283 mg of *endo-trans*-5-methyl-6-phenylbicyclo[2.2.2]oct-2-ene as a colorless oil: GC/MS *m/e* (rel abundance) 198 (6), 119 (10), 118 (100), 117 (35), 115 (10), 91 (14), 80 (43), 79 (22), 77 (13); ^1H NMR δ 1.06 (d, 2 H, $J = 6.0$), 1.09–1.18 (m, 1 H), 1.23–1.33 (m, 1 H), 1.60–1.69 (m, 2 H), 1.76–1.83 (7, 1 H), 2.19 (d, 1 H, $J = 9.0$), 2.30–2.32 (m, 1 H), 2.50–2.52 (m, 1 H), 6.23 (dd, 1 H, $J_1 = J_2 = 7.5$), 6.50 (dd, 1 H, $J_1 = J_2 = 7.5$), 7.13–7.30 (m, 5 H). Anal. Calcd for $C_{15}H_{18}$: C, 90.85; H, 9.15. Found: C, 90.78; H, 9.19.

The *exo* aldehyde was reduced in similar fashion with the exception that a 85% hydrazine hydrate solution was used in place of the 55% solution. Filtration through silica gel yielded 306 mg of colorless oil: GC/MS *m/e* (rel abundance) 198 (6), 119 (10), 118 (100), 117 (36), 115 (10), 91 (14), 80 (45), 79 (23), 77 (12); ^1H NMR δ 0.85 (d, 3H, $J = 6.0$), 0.90–0.99 (m, 1 H), 1.32–1.41 (m, 1 H), 1.53–1.68 (m, 2 H), 1.96–2.01 (m, 1 H), 2.21–2.23 (m, 1 H), 2.35–2.43 (m, 2 H), 6.22 (dd, 1 H, $J_1 = J_2 = 7.5$), 6.43 (dd, 1 H, $J_1 = J_2 = 7.5$), 7.16–7.40 (m, 5 H); exact mass calcd for $C_{15}H_{18}$ 198.1409, found 198.1403.

Identification of Endo and Exo Trans Stereoisomers. A 1.0-g portion of the (to-be-shown) *exo*-phenyl aldehyde was reduced with $LiAlH_4$ to the alcohol (900 mg crude yield) and purified by recrystallization from hexane to give a white solid: GC/MS *m/e* (rel abundance) 214 (6), 134 (34), 118 (25), 115 (10), 92 (32), 91 (15), 80 (100), 79 (35), 78 (10), 77 (16); ^1H NMR δ 0.96–1.04 (m, 1 H), 1.20 (s, 1 H), 1.33–1.46 (m, 1 H), 1.59–1.71 (m, 2 H), 2.11–2.24 (m, 2 H), 2.40–2.41 (m, 1 H), 2.78–2.79 (m, 1 H), 3.25–3.37 (m, 2 H), 6.23 (dd, 1 H, $J_1 = J_2 = 7.5$), 6.47 (dd, 1 H, $J_1 = J_2 = 7.5$), 7.18–7.38 (m, 5 H); ^{13}C NMR δ 18.5, 26.0, 31.8, 37.6, 45.3, 47.1, 67.2, 126.1, 128.3, 128.3, 131.7, 136.0, 143.1. Anal. Calcd for $C_{15}H_{18}O$: C, 84.07; H, 8.47. Found: C, 84.04; H, 8.50.

The *endo*-phenyl stereochemistry of this alcohol was proven by its bromoetherification. The bicyclic alcohol (200 mg, 0.93 mol) was dissolved in 10 mL of CH_2Cl_2, pyridine (0.08 mL, 0.93 mmol) was added to the solution, and the reaction mixture was cooled to 0 °C. A solution (5 mL) of 0.1 mL of Br_2 in 10 mL of CCl_4 was added dropwise. The reaction solution was stirred at 0 °C

(15) Mattes, S. L.; Farid, S. *Acc. Chem. Res.* **1982**, *15*, 80. Weller, A. *Fast React. Primary Processes Kinet. Proc. Nobel Symp. 5th* **1967**, 413. Rehm, D.; Weller, A. *Ber. Bunsen-Ges. Phys. Chem.* **1969**, *73*, 834. Weller, A. *Pure Appl. Chem.* **1982**, *54*, 1885. Gordon, M.; Ware, W. R. *The Exciplex*; Academic: New York, 1975. Masuhara, H.; Mataga, N. *Acc. Chem. Res.* **1981**, *14*, 312. Ohta, H. Creed, D.; Wine, P. H.; Caldwell, R. A.; Melton, L. A. *J. Am. Chem. Soc.* **1976**, *98*, 2002. Creed, D.; Caldwell, R. A.; Ohta, H.; DeMarco, D. C. *J. Am. Chem. Soc.* **1977**, *99*, 277.

(16) Hudrlik, P. F.; Tacacs, J. M. *J. Org. Chem.* **1978**, *43*, 3861. Walshe, N. D. A.; Goodwin, G. B. T.; Smith, G. C.; Woodward, F. E. *Org. Synth.* **1986**, *65*, 1. Ainsworth, C.; Chen, F.; Kuo, Y. N. *J. Organomet. Chem.* **1972**, *46*, 59.

(17) Cashin, C. H.; Fairhurst, J.; Horwell, D. C.; Pallas, I. A.; Sutton, S.; Timmus, G. H.; Wildsmith, E.; Wright, F. *Eur. J. Med. Chem.* **1978**, *13*, 495.

(18) Huang-Minlon, *J. Am. Chem. Soc.* **1949**, *71*, 3301.

for 40 min, diluted with CH_2Cl_2, and then washed twice with H_2O. The combined aqueous layers were back-extracted with CH_2Cl_2 and dried, and the solvent was removed. The crude product, an orange oil, was purified by spinning-disk chromatography on silica gel eluted with 15% EtOAc–hexane to yield, after recrystallization from hexane, 130 mg of bromo ether: GC/MS *m/e* (rel abundance) 294 (1), 292 (1), 214 (18), 213 (100), 196 (12), 195 (79), 183 (26), 167 (13), 155 (46), 141 (35), 133 (17), 129 (23), 128 (18), 117 (63), 116 (12), 115 (48), 105 (16), 92 (11), 91 (74), 81 (12), 79 (41), 78 (11), 77 (26), 69 (13), 67 (15), 65 (13), 53 (13), 51 (16); ^1H NMR δ 1.30–1.38 (m, 1 H), 1.65–1.70 (m, 1 H), 1.82–1.89 (m, 3 H), 2.16–2.18 (m, 1 H), 2.54–2.57 (m, 1 H), 2.78–2.79 (m, 1 H), 3.57 (d, 1 H, J = 9), 3.74–3.78 (dd, 1 H), 4.10 (d, 1 H, J = 3.0), 4.35 (d, 1 H, J = 6.0), 7.22–7.42 (m, 5 H); ^{13}C NMR δ 13.3, 14.6, 35.5, 36.5, 38.7, 49.1, 58.3, 82.3, 126.3, 127.9, 128.4, 143.3. Anal. Calcd for $C_{15}H_{17}OBr$: C, 61.45; H, 5.84; Br, 27.25. Found: C, 61.43; H, 5.85; Br, 27.44.

Preparation of Authentic *endo-cis*-5-Methyl-6-phenylbicyclo[2.2.2]oct-2-ene. A degassed solution of *cis*-ethyl cinnamate[19] (1.90 g, 10.8 mmol), CHD (2.50 g, 31.3 mmol), and 114 mg of hydroquinone in a sealed thick-wall Pyrex tube was heated at 180 °C for 14 h. Since the cinnamate and its adduct with CHD were not easily separable, the two esters were isolated as a mixture after silica gel chromatography with benzene: GC/MS (of the adduct) *m/e* (rel abundance) 256 (4), 182 (38), 178 (10), 77 (72), 131 (59), 102 (12), 91 (13), 80 (100), 79 (32), 77 (19). The mixture of esters (1.05 g) was dissolved in ether and slowly added to $LiAlH_4$ (240 mg) in ether at 0 °C. After 1 h the reaction was quenched with EtOAc, washed twice with H_2O, twice with 20% acetic acid, and finally with saturated $NaHCO_3$ and then H_2O. The ether layer was dried, and the solvent was removed in vacuo leaving 790 mg of a mixture of cinnamyl alcohol and the bicyclic alcohol. Chromatography on silica gel, eluting with 10% EtOAc–hexane, gave 300 mg of an oil that solidified upon standing. The solid was recrystallized from hexane to give *endo-cis*-5-(hydroxymethyl)-6-phenylbicyclo[2.2.2]oct-2-ene as a white powder: GC/MS *m/e* (rel abundance) 214 (2), 118 (20), 92 (14), 91 (2), 80 (100), 79 (32), 77 (13); ^1H NMR δ 0.81 (br s, 1 H), 1.28–1.41 (m, 2 H), 1.64–1.74 (m, 2 H), 2.35–2.40 (m, 1 H), 2.67–2.74 (m, 2 H), 3.21 (d, 1 H, J = 12), 6.31 (dd, 1 H, $J_1 = J_2$ = 7.5), 6.55 (dd, 1 H, $J_1 = J_2$ = 7.5), 7.16–7.30 (m, 5 H); ^{13}C NMR δ 24.4, 27.7, 33.0, 36.4, 48.0, 48.2, 65.1, 126.2, 128.1, 128.6, 133.0, 134.0, 142.9. Anal. Calcd for $C_{15H18}O$: C, 84.07; H, 8.47. Found: C, 84.09; H, 8.60.

The bicyclic alcohol (181 mg) was dissolved in 15 mL of pyridine and cooled to 0 °C, and *p*-toluenesulfonyl chloride (348 mg) was added to the reaction mixture. After 20 h the reaction mixture was poured onto 75 g of ice and water and stirred for 15 min. The ice water was extracted three times with ether, the combined ether layers were washed twice with dilute HCl and dried, and the solvent was removed, leaving the crude tosylate; 260 mg as a tan oil.

The tosylate was reduced to *endo-cis*-5-methyl-6-phenylbicyclo[2.2.2]oct-2-ene with $LiEt_3BH_3$.[20] A solution of the crude tosylate (262 mg, 0.7 mmol) in THF (10 mL) was cooled to 0 °C, and $LiEt_3BH_3$ (1 M, 1.4 mL) was added via syringe. The solution was stirred at 0 °C for 1 h, kept at room temperature for 1 h, and then heated at reflux for 2 h. The reaction mixture was cooled to 0 °C and quenched with water, and then 2 mL of 3 N NaOH and 2 mL of 30% H_2O_2 were added. The crude product was extracted with pentane, the combined pentane extracts were washed with water and dried, and the solvent was removed. The remaining yellow oil was filtered through a pad of silica gel with pentane to give 95 mg of a clear colorless oil: GC/MS *m/e* (rel abundance) 198 (7), 118 (70), 117 (33), 115 (12), 91 (16), 80 (100), 79 (28), 77 (13); ^1H NMR δ 0.40 (d, 2 H, J = 9.0), 1.25–1.38 (m, 2 H), 1.64–1.70 (m, 2 H), 2.25–2.35 (m, 1 H), 2.46–2.47 (m, 1 H), 3.14 (d, 1 H, J = 12.0), 6.27 (dd, 2 H, $J_1 = J_2$ = 6.0), 6.52 (dd, 2 H, $J_1 = J_2$ = 6.0), 7.12–7.23 (m, 5 H). Anal. Calcd for $C_{15}H_{18}$: C, 90.85; H, 9.15. Found: C, 90.71; H, 9.13.

DCA-Sensitized Photolysis of 1-Methoxy-1-(trimethylsiloxy)ethene with CHD. The photochemical reaction was carried out as described above for the general case with 0.86 M ketene acetal and 0.21 M CHD in benzene solution. After 15 h of irradiation in the Rayonet photoreactor, the solvent was removed, the residue was dissolved in 5 mL of CH_2Cl_2, 10 mL of a 1% aqueous HCl solution was added, and the mixture was stirred at room temperature for 1.5 h. The reaction mixture was washed with a $NaHCO_3$ solution, dried, and analyzed by GC/MS as described above. The products were identified as CHD dimers, bicyclo[2.2.2]oct-5-en-2-one (minor) and bicyclo[4.2.0]oct-2-en-8-one (major) by comparison with authentic samples.[21] The major ketone product was hydrogenated before comparison with the authentic sample. A 100-mg portion of a mixture of the endo and exo isomers of the major ketone product was reduced in ethyl acetate solution containing 5 mg of 5% Pd/C catalyst under 1 atm of H_2 for 12 h. The catalyst was removed by filtration, and the product was analyzed by GC/MS and shown to be identical with an independently prepared sample of bicyclo[4.2.0]octan-7-one.[21]

DCA-Sensitized Photolysis of 1-(Trimethylsiloxy)-1-phenylethene with CHD. The irradiation was carried out as described above: a benzene solution of the enol ether (0.86 M) and CHD (0.21 M) was photolyzed in the Rayonet for 15 h. After irradiation, analysis by GC/MS showed four products that correspond to adducts of CHD to the enol ether. These products were purified by chromatography on silica gel (0.7% EtOAc–hexane) and shown to be the endo and exo isomers of 5-(trimethylsiloxy)-5-phenylbicyclo[2.2.2]oct-2-ene: (phenyl endo isomer) ^1H NMR δ (CD_2Cl_2) –0.08 (s, 9 H), 1.02–1.37, 1.62–1.82, 2.22–2.37 (7, 6 H), 2.70–2.57 (m, 2 H), 5.81–5.86 (m, 1 H), 6.09–6.17 (m, 1 H), 7.12–7.52 (m, 5 H); MS *m/e* 272, 257, 231, 191, 177, 135, 105, 77, 75, 73, 45. Anal. Calcd for $C_{17}H_{24}OSi$: C, 75.07; H, 8.89. Found: C, 75.28; H, 8.99. For the phenyl exo isomer, the ^1H NMR spectrum shows only one peak for the vinyl protons, a multiplet at δ 6.28–6.38. The structures of these compounds were confirmed by their hydrogenation to 2-phenyl-2-(trimethylsiloxy)bicyclo-[2.2.2]octane, which was prepared independently.[22]

The [2 + 2] cycloaddition products, *endo*- and *exo*-8-(trimethylsiloxy)-8-phenylbicyclo[4.2.0]oct-3-ene, were isolated by chromatography on silica gel: (phenyl endo isomer) ^1H NMR (C_DCl_2) δ –0.01 (s, 9 H), 1.43–1.68, 1.93–2.05, 2.1–2.2, 2.45–2.60, 2.9–3.1 (7, 8 H), 5.20–5.32 (7, 1 H), 5.56–5.66 (m, 1 H), 7.50–7.60 (m, 5 H); (phenyl exo isomer) ^1H NMR (CD_2Cl_2) δ –0.01 (s, 9 H), 1.35–1.65, 2.10–2.30, 2.52–2.63, 2.82–2.92 (m, 8 H), 5.84–6.00 (m, 2 H), 7.21–7.60 (m, 5 H). The structures were confirmed by comparison with authentic samples after catalytic hydrogenation.

Preparation of Authentic Samples of *endo*- and *exo*-2-(Trimethylsiloxy)-2-phenylbicyclo[2.2.2]oct-2-ene and *endo*- and *exo*-2-(Trimethylsiloxy)-2-phenylbicyclo[4.2.0]octane. A mixture of *endo*- and *exo*-5-phenylbicyclo[2.2.2]oct-2-en-5-ols (2.42 g 12.1 mmol) was prepared[22] and dissolved in CH_2Cl_2 (10 mL) containing 1.24 g (15.6 mmol) of pyridine. A solution of $(CH_3)_3SiCl$ (1.70 g, 15.7 mmol) in 10 mL of CH_2Cl_2 was added slowly to the reaction solution. After 2 h at room temperature the reaction mixture was poured into water, and the resulting mixture was extracted three times with CH_2Cl_2. The combined extracts were dried, and the solvent was removed to leave 2.5 g of crude *exo*- and *endo*-5-(trimethylsiloxy)-5-phenylbicyclo-[2.2.2]oct-2-enes. The crude reaction product (190 mg) was hydrogenated with Pd/C in ethyl acetate to give 2-(trimethylsiloxy)-2-phenylbicyclo[2.2.2]octane. This compound was identical by GC/MS with the product obtained from hydrogenation of the isolated products from the triplex reaction. The authentic [2 + 2] photoadducts were prepared by BP-sensitized addition of the enol ether to CHD. The crude photolysis mixture was purified by chromatography on silica gel to give the exo and endo isomers of 5-(trimethylsiloxy)-5-phenylbicyclo[2.2.2]oct-2-enes that were identical with the products from the triplex procedure.

DCA-Sensitized Photolysis of 1-(Trimethylsiloxy)-1-phenylethene with CPD. The irradiation was carried out as described above: a benzene solution of the enol ether (0.53 M) and CPD (0.27 M) was photolyzed in the Rayonet for 18 h. After irradiation, analysis by GC/MS showed four products that correspond to adducts of CHD and the enol ether. The major

(19) Lindlar, H.; Dubuis, I. *Org. Synth.* **1973**, *5*, 880.
(20) Tipson, R. S. *J. Org. Chem.* **1944**, *9*, 235.
(21) Ghosez, Li; Montaigne, R.; Roussel, A.; Vanlierde, H.; Mollet, P. *Tetrahedron* **1971**, *27*, 615.
(22) Snowden, R. L.; Schulte-Elte, K. H. *Helv. Chim. Acta* **1981**, *64*, 2193.

products were shown to be the exo and endo isomers of 5-phenyl-5-(trimethylsiloxy)bicyclo[2.2.1]hept-2-ene by their conversion to 2-phenylbicyclo[2.2.1]hepta-2,5-diene[23] by reaction with a mixture of CF_3CO_2H in CH_3CO_2H at room temperature for 3.5 h.

DCA-Sensitized Photolysis of 1-(Trimethylsiloxy)-1-phenylethene with CHpD. The irradiation was carried out as described above: a benzene solution of the enol ether (0.61 M) and CHpD (0.34 M) was photolyzed in the Rayonet for 17 h. Analysis of the crude reaction mixture by GC/MS showed four 1:1 adducts of CHpD to the enol ether. The crude reaction mixture was hydrolyzed and dehydrated as above to give 6-phenylbicyclo[3.2.2]nona-6,8-diene as the minor product, which was identified by comparison with an authentic sample prepared from 8-(trimethylsiloxy)-8-phenylbicyclo[3.2.2]non-6-ene: ^1H NMR (200 MHz, CD_2Cl_2) δ 0.06 (s, 9 H), 1.4–1.9, 2.1–2.2, 2.46–2.85 (m, 10 H), 5.57–5.68 (m, 1 H), 5.9–6.0 (m, 1 H), 7.10–7.64 (m, 5 H); GC/MS *m/e* 286, 192, 177, 153, 135, 91, 75, 73. The major product of this reaction is 9-phenylbibyclo[5.2.0]nona-2,8-diene.

Preparation of Authentic 2-Phenylbicyclo[2.2.2]octa-2,5-diene. 2-Phenylbicyclo[2.2.2]octan-5-en-2-ol was prepared in the standard way by reaction of bicyclo[2.2.2]oct-5-en-2-one (0.95 mol) with phenylmagnesium bromide in 2 mL of ether: GC/MS (EI) *m/e* (rel abundance) 200 (2, m^+), 182 (10), 154 (100). The alcohol was converted to its tosylate in the usual way and then heated at 80 °C for 12 h to complete elimination to the diene. The crude product was purified by chromatography on silica gel with 20% ethyl acetate in hexane: ^1H NMR ($CDCl_3$) δ 7.2–7.4 (m, 5 H), 6.53 (dd, J_1 = 6.3, J_2 = 2.1, 1 H), 6.46 (m, 2 H), 4.15 (m, 1 H), 3.7 (m, 1 H), 1.6–1.3 (m, 4 H); GC/MS (EI) *m/e* (rel abundance) 182 (3, m^+), 154 (100).

TCA-Sensitized Photolysis of DMBD and Phenylpropyne. A saturated dioxane solution of TCA, phenylpropyne (0.4 M), and DMBD (0.2M) was irradiated in the usual way. Only one crossed cycloadduct was detected by GC/MS. The product was isolated by fractional distillation under vacuum to give pale yellow oil: ^1H NMR (C_6D_6) δ 7.38–6.97 (m, 5 H), 4.985 (d, J = 3, 1 H), 4.865 (d, J = 3, 1 H), 2.315 (d, J = 15, 1 H), 2.065 (d, J = 15, 1 H), 1.74 (s, 3 H), 1.69 (s, 3 H), 1.47 (s, 3 H); ^{13}C NMR (C_6D_6) δ 149.7, 143.8, 136.3, 135.5, 126.9, 125.9, 109.8, 48.1, 44.6, 22.1, 19.2, 15.4; $C_{15}H_{18}$ MS *m/e* calcd 198.1409, found 198.1408; GC/MS *m/e* (rel abundance) 198.10 (36), 183.10 (100), 168.10 (38).

Synthesis of *trans*-2-Methyl-3-phenylbicyclo[2.2.2]octane. A portion of previously prepared *endo-trans*-5-methyl-6-phenylbicyclo[2.2.2]oct-2-ene (206 mg, 1.0 mmol) was dissolved in 20 mL of ethyl acetate in a thick-walled glass vessel. A catalytic amount of Pd/C was added to the solution, and the solution was agitated under 50 psi of H_2. After 30 min of reaction, the pressure was released, the catalyst was removed by filtration, the solvent was removed, and the resulting oil was distilled and filtered through silica gel with pentane. The product (30 mg) is a colorless oil: GC/HS *m/e* (rel abund) 200 (100), 118 (52), 117 (51), 115 (36), 109 (90), 91 (65), 67 (44). ^1H NMR δ 0.97 (d, 3 H, J = 6.6), 1.2–1.8 (m, 10 H), 2.04–2.09 (m, 1 H), 2.36 (d, 1 H, J = 8.1), 7.15–7.35 (m, 5 H). Anal. Calcd for $C_{15}H_{20}$: C, 89.94; H, 10.06. Found: C, 90.01; H, 10.03.

TCA Sensitized Photolysis of Phenylallene and CHD. The reaction was carried out as described above for the general case with a solution of phenylallene[24] (0.17 M) and CHD (0.24 M) in dioxane with hexadecane included as an internal standard. Following photolysis, the reaction mixture was hydrogenated with Pd/C as the catalyst, and yields of the adducts were determined by gas chromatography by comparison with authentic samples.

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(23) Baumgartel, O.; Szeimies, G. *Chem. Ber.* **1983**, *116*, 2180.

(24) Searles, S.; Li, Y.; Nassim, B.; Lopes, M. T.; Tran, P.; Crabbe, P. *J. Chem. Soc., Perkin Trans. 1* **1984**, 747.

Kinetics and Mechanisms for Reactions of Adenosine 2′- and 3′-Monophosphates in Aqueous Acid: Competition between Phosphate Migration, Dephosphorylation, and Depurination

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First-order rate constants for mutual isomerization, hydrolytic dephosphorylation, and depurination of adenosine 2′- and 3′-monophosphates have been determined by HPLC over a wide pH range. The interconversion of 2′- and 3′-AMP is first order with respect to hydronium ion at pH < 1, approaches a second-order dependence at 1 < pH < 2, and becomes pH independent at 3 < pH < 6. The resulting equilibrium mixture contains 30% of 2′-AMP and 70% of 3′-AMP. Hydrolysis of cyclic 2′,3′-AMP has been observed to give the same product distribution. Hydrolytic dephosphorylation competes with the phosphate migration at 2 < pH < 6 and acidic depurination at pH < 3. The reactive ionic forms have been deduced from the shapes of the pH–rate profiles obtained. Incorporation of ^{18}O from solvent water into 2′- and 3′-AMP has been shown to be considerably slower than their acid-catalyzed interconversion, which excludes the reaction via cyclic 2′,3′-monophosphate as the main pathway.

Introduction

It has been known since the early 1950s that nucleoside 2′- and 3′-monophosphates undergo a mutual isomerization in aqueous acid.[1,2] However, surprisingly little attention has been paid to the kinetics and mechanism of this reaction. In fact, the available kinetic data are limited to the semiquantitative observation of Abrash et al.,[3] according to which uridine cyclic-2′,3′-monophosphate is hydrolyzed to a mixture of uridine 2′- and 3′-monophosphates about 10 times faster than the latter nucleo-

(1) Brown, D. M.; Todd, A. R. *J. Chem. Soc.* **1952**, 52.
(2) Cohn, W. E. *J. Am. Chem. Soc.* **1950**, *72*, 2811.
(3) Abrash, H. I.; Cheung, C.-C. S.; Davis, J. C. *Biochemistry* **1967**, *6*, 1298.

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