Reaction of Cyclic Olefins with Acetyl Nitrate. [2 + 2] Cycloaddition of the Nitryl Cation?

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Abstract: The reactions of $AcONO_2$ with the cyclic olefins cyclopentene, cyclohexene, *cis*-cyclooctene, methylenecyclobutane, and norbornene have been investigated or, in some cases, reinvestigated. Although many products are formed, material balances in the order of 80% have been achieved in all cases, and structures have been assigned to the products. In contrast to previous results, 1,2-addition is found to be always a minor pathway, which is accompanied by 1,3- and 1,4-addition and the formation of allylic and homoallylic nitroalkenes. Methylenecyclobutane and norbornene react with skeletal rearrangement. Although such observations seem characteristic of carbocationic processes, the absence of conjugated nitroalkenes from the reaction mixtures, together with a demonstration that such compounds are stable under the reaction conditions, indicates that the primary process cannot consist of the formation of a β-nitrocarbocation. A new mechanistic proposal has, therefore, been advanced, which involves an initial [2 + 2] addition of NO_2^+ to the double bond. Ring-opening, rearrangement, and elimination reactions of the putative species **1** are then shown to account for all of the results. These various proposals are consistent with theoretical calculations and with the behavior of related systems, in which intramolecular rearrangement or elimination from intermediate species is not in doubt.

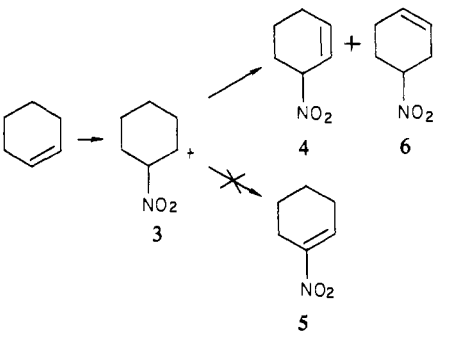
Thermal [2 + 2] cycloaddition or cycloreversion reactions proceed most readily when at least one of the reactants or products contains a linear unsaturated system XYZ having the general structure

$$X{=}Y{=}Z,\ X{-}\overset{+}{Y}{=}Z,\ \text{or}\ X{-}\overset{+}{Y}{\equiv}Z$$

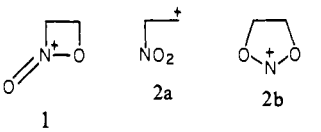
As first discussed by Woodward and Hoffmann,[3] the presence of this moiety facilitates the perpendicular approach characteristic of a concerted [2s + 2a] process. There are now numerous combinations of X, Y, and Z for which such reactions appear to occur.[4]

This paper is concerned with the reactions of acetyl nitrate ($AcONO_2$) with the series of cyclic monoolefins methylenecyclobutane, cyclopentene, cyclohexene, cyclooctene, and norbornene in acetic anhydride solvent. In each case, a materials balance in the order of 75-85% has been obtained, and the many products have been characterized. All of the results can be accommodated to the postulate that the primary reaction of acetyl nitrate with these substrates consists of a [2 + 2] addition of the linear nitryl cation (NO_2^+) to the carbon-carbon double bond to form the cyclic 2-isoxazetidinonyl cation **1**.

Scheme I



3 4 5 6



1 2a 2b

Acetyl nitrate was first obtained by the equilibration of acetic anhydride with nitrogen pentoxide[5] but is prepared more conveniently in situ by addition of nitric acid to acetic anhydride. The resulting reagent has been found to react with olefinic double bonds in the following manner:[6] (i) 1,2-nitro acetates are formed in 20-65% yield, depending upon the structure of the olefin; (ii) the

(1) Moscow State University.
(2) Queen's University.
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Table I. Computed Energetics of the C_2H_4–NO_2^+ Surface

system	total energy[b]		relative energy[c]	
	3-21G//3-21G	6-31G*//3-21G	3-21G//3-21G	6-31G*//3-21G
$C_2H_4 + NO_2^+$	−280.061045[d]	−281.707141[e]	0.0	0.0
1	−280.189989	−281.790902	−80.91	−52.56
2a	−280.096958[f]	−281.715549	−22.54	−5.28
2b	−280.218898[g]	−281.813772	−99.05	−66.91

[a] All structures have been fully optimized at the 3-21G level. [b] In atomic units (1 au = 627.5 kcal/mol). [c] In kcal/mol. [d] Individual energies are: C_2H_4, −77.600989; NO_2^+, −202.460056. [e] Individual energies: C_2H_4, −78.031695; NO_2^+, −203.675546. [f] Optimized parameters: C–C, 1.458; C–N, 1.610; N–O, 1.220; $^+$C–H, 1.078; C–H, 1.076; ∠NCC, 99.54; ∠ONC, 114.13; ∠ONCC, 90.03; ∠H–C$^+$–C, 120.58; ∠H–C–C$^+$, 114.90. [g] Optimized parameters are: C–C, 1.538; C–O, 1.535; N–O, 1.287; C–H, 1.074; ∠CCO, 101.08; ∠ONO, 111.54; ∠NOC, 113.15; ∠HCC, 115.23.

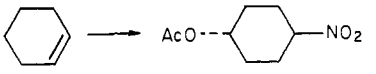
reaction mixtures also contain 1,2-nitro nitrates and nitroolefins; (iii) the 1,2-nitro acetates may be formed by cis addition, by trans addition, or both.

Bordwell and Garbisch[6c] considered the possible role of the cycloadduct **1** but could not account for cis addition in terms of this species. Moreover, it was argued, the four-membered ring would be formed at the expense of the resonance stabilization of NO_2^+.

Stereospecific cis addition was also considered[6c] to be inconsistent with the formation of a β-nitro carbocationic intermediate such as **2a**. Moreover, as depicted in Scheme I for the reaction of cyclohexene, the nitroolefin products invariably have the unconjugated (cf. **4**) rather than the conjugated structure of **5**. Deprotonation of **3** should have led to **5**.[6f]

However, later work by Griswold and Starcher[6g] revealed that, although the nitroolefins afforded by cyclohexene and cyclopentene do not contain the conjugated isomer, both the allylic (cf. **4**) *and the homoallylic* isomers (cf. **6**) are present. It is not surprising that the reaction of acetyl nitrate with olefins has been termed[6i] "a source of nightmares for those who would attempt a coherent description".

Very recently,[7] it was discovered that cyclohexene yields, inter alia, the 1,4-nitro acetate **7**, and that norbornene reacts with



7

skeletal rearrangement. These observations prompted the present reexamination of the problem.

Theoretical Considerations

Bernardi and Hehre[8a] have performed calculations on the C_2H_4–NO_2^+ energy surface. In the gas phase, the cycloadducts **1** and **2b** were found to be local minima, some 60 kcal/mol lower in energy than the acyclic cation **2a**. These findings are not necessarily incompatible with Bordwell and Garbisch's argument[6c] concerning the relative stabilities of **1** and **2a**: the very large heats of transfer of carbocations from the gas phase to solution[9] might well cause a cyclic (internally solvated) cation to possess relative stability in the gas phase, but an acyclic (externally solvated) cation could possess relative stability in solution.[10]

Unfortunately, the geometries and energies of **1** (see Figure 1 and Table I), **2a**, and **2b** were not reported in ref 8a and are now not available.[8b] Therefore, in view of the interest in **1** that developed during the present work, it was considered necessary to repeat and extend the earlier calculations. GAUSSIAN 80,[11] which

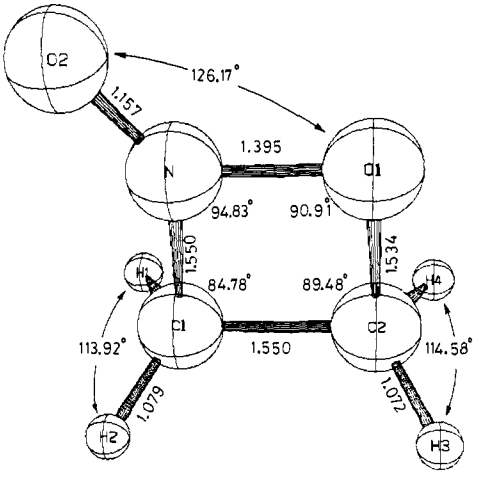


Figure 1. ORTEP structure of the [2 + 2] adduct **1**.

contains efficient gradient procedures[12] for the complete optimization of all geometrical parameters as well as contemporary basis sets for comparisons of energy differences, was used to locate stationary points corresponding to structures **1**, **2a**, and **2b** at the 3-21G level (3-21G//3-21G), and single point calculations were then performed on these optimized structures at the 6-31G* level (6-31G*//3-21G). To check whether **1**, **2a**, and **2b** represent energy minima or energy maxima, Professor W. J. Hehre kindly calculated the second derivative (force constant) matrix of each structure[13] by using GAUSSIAN 83.[14] These force constant calculations revealed no negative eigenvalues for the cyclic structures **1** and **2b** and one negative eigenvalue for the acyclic structure **2a**. The cyclic structures are, therefore, energy minima in the gas phase, but the acyclic structure is an energy maximum.

The various energies and energy differences now computed are summarized in Table I, and Figure 1 shows the ORTEP structure of **1**.[15,16]

Results

Addition to Cyclopentene. The previous workers[6c,g] reported the products to be 1,2-nitro acetate (15–20%), 1,2-nitro nitrate (4–8%), and nitro cyclopentenes (13%). In our hands the reaction repeatedly led to a 1:1 mixture of allylic (**8**) and homoallylic (**9**) nitrocyclopentenes (19%), the *cis*-1,3-nitro acetate **10** (17%), the *trans*-1,3-nitro acetate **11** (26%), and the *trans*-1,3-nitro nitrate **12** (8%). The 1,2-nitro acetate **13** was isolated *in only 5% yield*.[17]

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(15) Johnson, C. K. ORTEP, Report ORNL-3974, revised. Oak Ridge National Laboratory, TN, 1965.
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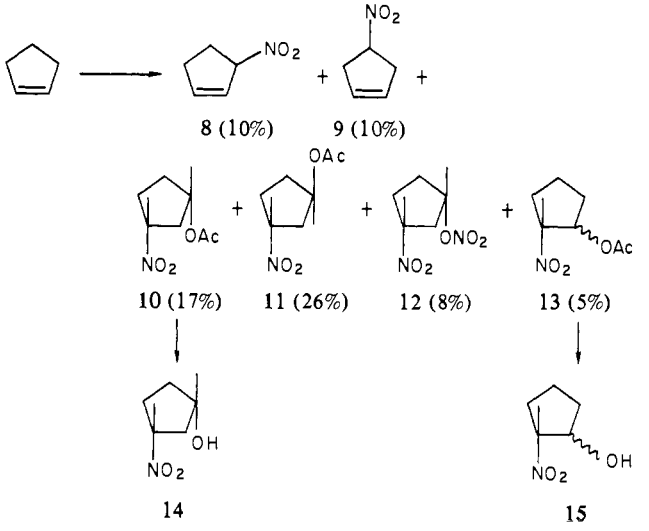
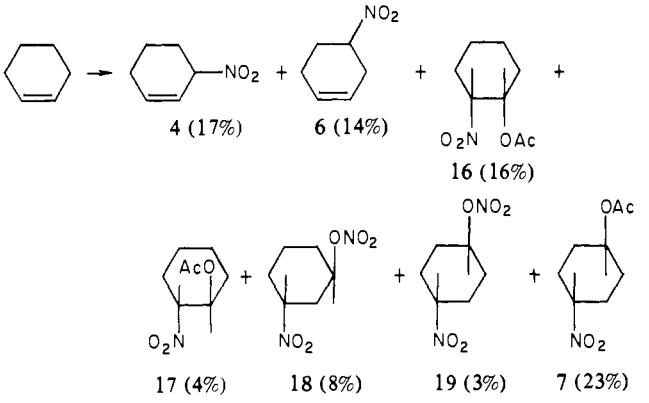
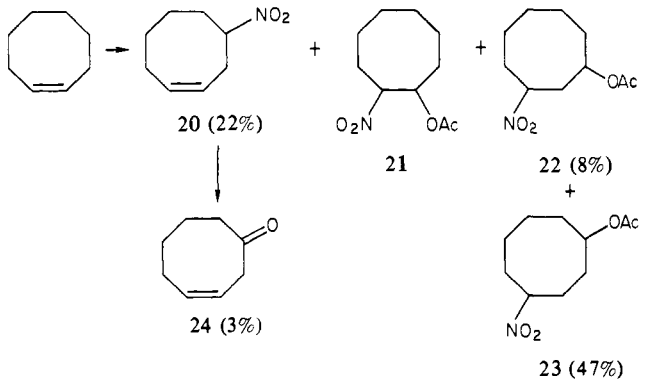


Addition to Cyclohexene. The previous workers[6c,g] obtained a mixture of β- and γ-nitrocyclohexenes (34%), 1,2-nitro acetate (21%) and 1,2-nitro nitrate (10%).

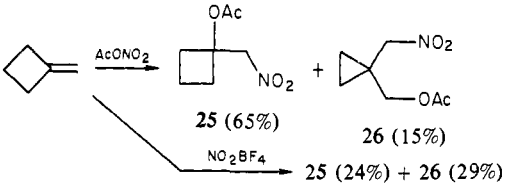
In the present work, the products are a 5:4 mixture of **4** and **6** (31%), a 4:1 mixture of *cis*- and *trans*-1,2-nitro acetates **16** and **17** (20%), *trans*-1,3-nitro nitrate **18** (8%), *trans*-1,4-nitro nitrate **19** (3%), and *trans*-1,4-nitro acetate **7** (23%). The latter compound could be partially crystallized directly from the reaction mixture after removal of the nitroolefins by distillation.[18]



Addition to *cis*-Cyclooctene. The products isolated from this reaction are 4-nitrocyclooctene (**20**) (22%), 1,2-nitro acetate **21** (8%), 1,3-nitro acetate **22** (3%), and 1,4-nitro acetate **23** (47%). No bicyclic products were found.[19]



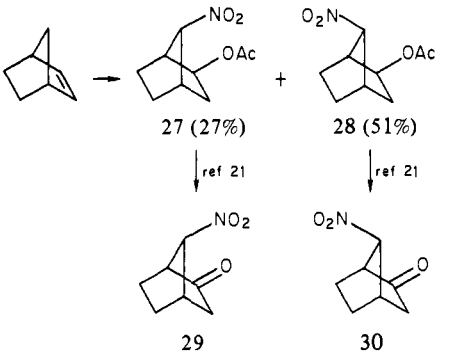
Addition to Methylenecyclobutane. This reaction afforded the unrearranged (**25**, 65%) and rearranged (**26**, 15%) nitro acetates.



The major product shows the ring protons as a multiplet near 2.40 ppm in addition to a low field singlet at 4.9 ppm. The compound is assigned the Markovnikov addition structure **25** on the basis of this latter chemical shift and comparison with the ^{1}H NMR spectrum of 1-acetoxy-1-(nitromethyl)cyclohexane, prepared by acetylation of the corresponding alcohol. The latter compound has a two-proton singlet at 4.86 ppm. That the minor product **26** is a cyclopropane is evident from the presence of a four-proton singlet at 0.86 ppm in addition to the two-proton singlets at 4.27 ppm (CH_2OAc) and 3.95 ppm (CH_2NO_2).

Addition of NO_2BF_4 in acetic anhydride was also examined. At −40 °C this led to a decrease in the unrearranged compound **25** (65% → 24%) and an increase in the rearranged compound **26** (15% → 29%).

Addition to Norbornene. This reaction led to the *syn-exo*-nitro acetate **27** (27%) and the *anti-exo*-nitro acetate **28** (51%). In both compounds the proton geminal to nitro is observed as a singlet, so that the nitro substituent is attached to C7; the proton geminal to the acetoxy group is observed near 4.6 ppm as a doublet of doublets (J values were 7 Hz and 3 Hz). The data are consistent with the conclusion that the two compounds are epimeric at C7. The data may also be consistent with the conclusion that the compounds are epimeric at C2.[20] In a related study of the reaction of norbornene with NO_2BF_4 in acetic anhydride at −40 °C,[21] nitro acetates **27** and **28** were isolated in 34% and 51% yields, respectively, and the assignments of structures epimeric at C7 was confirmed by hydrolysis to nitro alcohols and chromic acid oxidation to *different* nitro ketones **29** and **30**. The nitro acetates obtained in the present work were found to be identical with those of the earlier study.



Discussion

As observed in most previous studies, the reaction of acetyl nitrate with the present series of olefins leads to nonstereospecific addition accompanied by skeletal rearrangement in the cases of methylenecyclobutane and norbornene and multiple hydride transfers in the cases of the monocyclic olefins. Such results would normally imply the intervention of carbocationic intermediates. However, the formation of such species is incompatible with the *absence of conjugated* nitroalkenes from the reaction mixtures when nitroalkenes are formed. This finding is in accord with all previous work; indeed, conjugated nitroalkenes have been detected

(17) See the supplementary material section for details of the structural assignments to compounds **8–13** and the derived alcohols **14** and **15**.

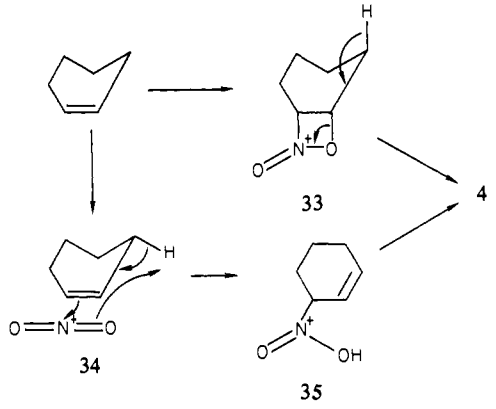
(18) See the supplementary material section for details of the structural assignments to compounds **4**, **6**, **7**, and **16–19**.

(19) See the supplementary material section for details of the structural assignments to **20–23** and the conversion of **20** to **24**.

(20) Marshall, J. L.; Walter, S. R.; Barfield, M.; Marchand, A. P.; Marchand, N. W.; Segre, A. L. *Tetrahedron* **1976**, *32*, 537–542.

(21) Zlotin, S. G.; Krayushkin, M. M.; Sevost'yanova, V. V.; Novikov, S. S. *Bull. Acad. Sci. USSR, Div. Chem. Sci. (Engl. Transl.)* **1977**, *26*, 2121–2127.

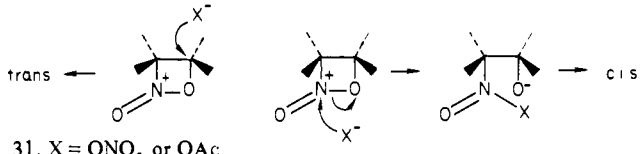
Scheme II



among the products only when one or more benzene rings are attached to the double bond[6e,f,h,j] and, even in such cases, as minor components of mixtures of conjugated and unconjugated nitroalkenes. There is only one example of the preferential formation of a conjugated nitroalkene[6j] in the case of a conformationally constrained styrene derivative and, in this special case, the yield was only 5%.

It is known[6f,22] that conjugated nitroalkenes are more stable than their unconjugated isomers. To check this point under the conditions of the acetyl nitrate reactions, 1-nitrocyclohexene was subjected to the usual reaction conditions and then reisolated. There was no isomerization. Consequently, it cannot be argued that 3- and 4-nitrocyclohexene are formed in the cyclohexene reaction at the expense of the 1-nitro isomer.

The simplest interpretation of the reactions of cyclopentene, cyclohexene, and cyclooctene is that these proceed via a [2 + 2] cycloadduct of type 1. Depending on the structure of the starting olefin, this adduct may react with acetate or nitrate to form 1,2-addition products. Attack at carbon (cf. **31**) leads to trans adducts. Attack at nitrogen (cf. **32**) leads, following N→O acetate or nitrate transfer[23,24] to cis adducts.

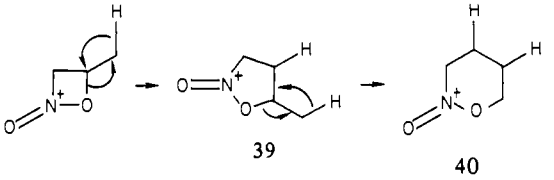


31, X = ONO_2 or OAc

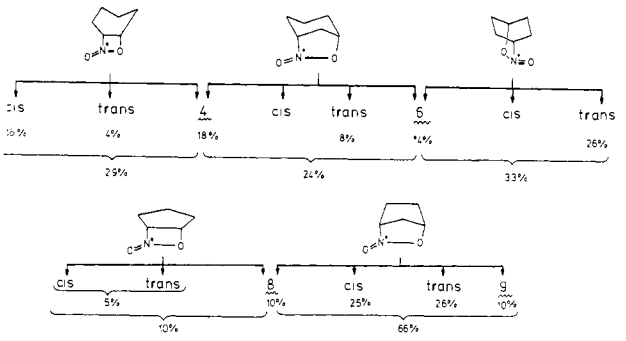
32, X = ONO_2 or OAc

As depicted in Scheme II for the cyclohexene cycloadduct **33**, proton loss from **33** leads to the β,γ-unsaturated nitro compound **4**. The sequence cyclohexene → **33** → **4** also corresponds to the ene reaction depicted in **34** → **35**. The distinction between a two-step cycloaddition–elimination sequence and a one-step ene reaction in related reactions has not been easy. In the reactions of olefins with singlet oxygen,[25,26] the most recent theoretical work suggests[27] that [2 + 2] addition is disfavored relative to the ene reaction. Perhaps more closely related to the present system is the conversion of olefins to β,γ-unsaturated ketones with acylium fluoroborates[28] or hexachloroantimonates.[29] Hoffmann and

Scheme III

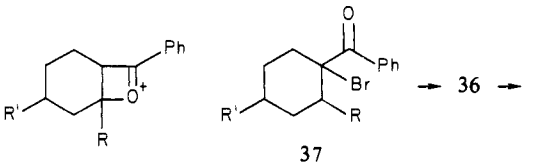


Scheme IV



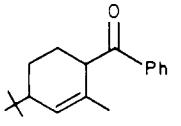
Tadahiko[29] have ruled out β-acyl carbocations as intermediates in such reactions because, as in the present work, α,β-unsaturated ketone formation can be completely suppressed. These workers favor an ene reaction.

An addition–elimination pathway in the reactions of acylium cations with, e.g., cyclohexene, would lead to the oxonium cation **36** (R = R′ = H) at an intermediate stage. Very significantly,



36

37



38

such species have been characterized by French workers[30] following the treatment of tertiary bromo ketones (cf. **37**, R = CH_3, R′ = H; R = CH_3, R′ = *t*-Bu) with silver hexafluoroantimonate in methylene chloride at −30 °C. In the latter case (R = CH_3, R′ = *t*-Bu), elimination occurs, at −30°C, to give the β,γ-unsaturated ketone **38** in 75% yield.

A cycloaddition–elimination pathway has also been suggested by Schönberger and Kresze[31] for the reaction of TsN=S=NTs with various olefins. These workers have commented upon the possible relevance of such results to the currently accepted ene reaction favored as the first step in allylic oxidation by selenium dioxide.[32] The chemistry of β-sultines,[33] β-sultones,[4v,34] and

(22) Schechter, H.; Shepherd, J. W. *J. Am. Chem. Soc.* **1954**, *76*, 3617–3621.

(23) Pavlova, L. V.; Rachinskii, F. Yu. *Russ. Chem. Rev.* (*Engl. Transl.*) **1968**, *37*, 587–602.

(24) Interestingly, in a footnote, Bordwell and Biranowski[6h] had earlier suggested a sequence close to that depicted in **32** but did not elaborate further upon the idea.

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(26) Stephenson, L. M.; Grdina, M. J.; Orfanopoulos, M. *Acc. Chem. Res.* **1980**, *13*, 419–425. Asveld, E. W. H.; Kellog, R. M. *J. Org. Chem.* **1982**, *47*, 1250–1257.

(27) Yamaguchi, K.; Fueno, T.; Saito, I.; Matsuura, T.; Houk, K. N. *Tetrahedron Lett.* **1981**, *22*, 749–752.

(28) Smit, W. A.; Semenovsky, A. V.; Kucherov, V. F.; Chernova, T. N.; Krimer, M. Z.; Lubinskaya, O. V. *Ibid.* **1971**, 3101–3106. Lubinskaya, O. V.; Shashkov, A. S.; Chertkov, V. A.; Smit, W. A. *Synthesis*, **1976**, 742–745.

(29) Hoffmann, H. M. R.; Tadahiko, T. *J. Am. Chem. Soc.* **1977**, *99*, 6008–6011.

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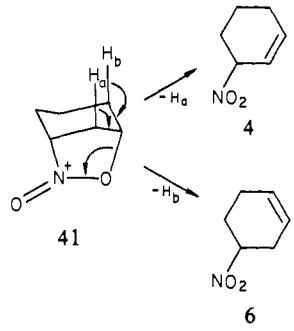
(32) Arigoni, D.; Vasella, A.; Sharpless, K. B.; Jensen, H. P. *J. Am. Chem. Soc.* **1973**, *95*, 7917–7919. Warpehoski, M. A.; Chabaud, B.; Sharpless, K. B. *J. Org. Chem.* **1982**, *47*, 2897–2900. Münsterer, H.; Kresze, G.; Brechbiel, M.; Kwart, H. *Ibid.* **1982**, *47*, 2679–2681.

(33) Jung, F.; Sharma, N. K.; Durst, T. *J. Am. Chem. Soc.* **1973**, *95*, 3420–3422. Durst, T.; Gimbarzevsky, B. P. *J. Chem. Soc., Chem. Commun.* **1975**, 724–725. Carlsen, L.; Snyder, J. P. *Tetrahedron Lett.* **1977**, 2045–2048. DeLucchi, O.; Lucchini, V. *J. Chem. Soc., Chem. Commun.* **1982**, 464–465.

β-lactones[35] provides additional precedent for the present proposal of a cycloaddition–elimination sequence leading to β,γ-unsaturated nitroalkenes.

Scheme III proposes successive rearrangement of a 2-isoxazetidinonyl cation to a 2-isoxazolinonyl cation **39** and a 2-isoxazinonyl cation **40**. We regard such rearrangements as formally analogous to the diaxial → diequatorial rearrangement[36,37] and note the analogies with the behavior of oxonium cations.[30,38]

At the stage of the four-membered ring **1**, the five-membered ring **39**, and the six-membered ring **40**, elimination to nitroalkenes may occur, in competition with trans or cis ring opening, as depicted in **31** and **32**. If it is assumed that, when elimination from two sites is possible (cf. **41**) both are observed, the results

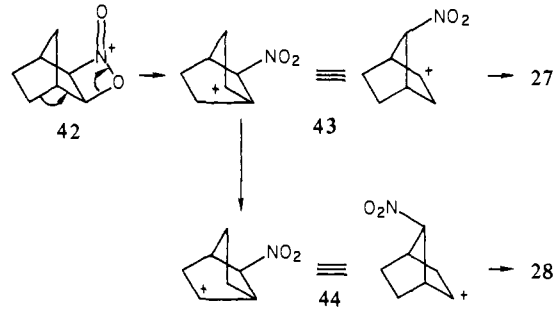


with cyclohexene and cyclopentene can be summarized as shown in Scheme IV. This leads to the following conclusions: (i) With cyclohexene, the four-membered heterocyclic ring, the five-membered heterocyclic ring, and the six-membered heterocyclic ring account respectively for 29%, 24%, and 33% of the products. (ii) The four-membered ring undergoes preferential cis opening but the five-membered and six-membered rings undergo preferential trans opening. (iii) With cyclopentene, the four-membered and five-membered heterocyclic rings account for 10% and 66% of the products. (iv) The bicyclo [2.2.1] system shows no preference for cis or trans opening, in contrast to the bicyclo [3.2.1] and bicyclo [2.2.2] systems in which trans opening is preferred.

In the case of cyclooctene, the same analysis suggests that most of the reaction proceeds via the six-membered heterocyclic ring with lesser contributions from the four-membered and five-membered rings. The absence of bicyclic products again reflects the absence of discrete carbocationic intermediates.

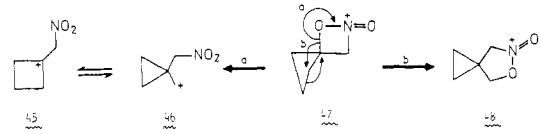
In terms of the foregoing analysis, the reaction of norbornene is anomalous, since the formation of the anti-exo adduct **28** cannot be interpreted in terms of a heterocyclic precursor. It is known[39] that [2 + 2] cycloaddition of neutral reactants to norbornene is impeded by substituents at C7. With a cationic reactant, it might be argued that the balance between cycloaddition and formation of a carbocation in the first step of the reaction is tipped in favor of the latter by the C7 hydrogens of norbornene. However, this would imply that the competition between the two paths in the case of NO_2^+ addition is balanced more closely than is apparent with any of the other substrates or in the theoretical calculations, even though these calculations refer to the gas phase. It seems more probable that the "normal" adduct **42** rearranges to the cation **43**, which now undergoes reactions typical of a norbornyl cation (e.g., hydride shift to form **44**).

With this interpretation, the behavior of **42** can be compared to that observed in sulfenyl halide addition to norbornene.[40] In



the presence of lithium perchlorate, the cationic character of the episulfonium intermediate is increased, with a concomitant increase in the proportion of rearranged vs. unrearranged products.

It is known[41,42] that the 1-methylcyclobutyl and 1-methylcyclopropylcarbinyl cations exist in rapid equilibrium, although the products derived from such systems are exclusively cyclobutanes. The reaction of methylenecyclobutane with acetyl nitrate affords mainly the cyclobutane **25**. This result is compatible with the formation of the cation **45** in the first step of the reaction, followed by equilibration to **46** and preferential capture of **45**.



The result is also compatible with the formation of the cycloadduct **47**, which may react with acetate to form **25** or rearrange to **46** via a, or, more interestingly, to **48** via b. The role of **48** in the formation of the cyclopropane **26** and, by extension, the existence of the cycloadduct **47** can be probed by deuterium labeling experiments. Such experiments are underway.

Experimental Section

The preparation of acetyl nitrate followed the procedure of Bordwell and Garbisch.[6c] The usual workup involved pouring the reaction mixture into ice-cold water, stirring for 1 h, and extracting with chloroform and then washing of these extracts with water, drying over $MgSO_4$ or Na_2SO_4, and removing the solvent under reduced pressure. Melting and boiling points are uncorrected. Full details of the reactions of cyclohexene, cyclooctene, norbornene, and methylenecyclobutane are available as supplementary material.

Reaction of Acetyl Nitrate with Cyclopentene. Ac_2O (100 mL), freshly distilled over P_2O_5, was cooled to 10 °C and 7.5 g (100 mmol) of HNO_3 (d = 1.38) was added dropwise with rapid stirring. The temperature was not allowed to exceed 26 °C. After the addition of HNO_3 was complete, the mixture was stirred for 15–20 min at room temperature and then cooled to −20 °C, and a solution of 3.4 g (50 mmol) of cyclopentene in 10 mL of Ac_2O was added during 1 min. The temperature of the reaction mixture rose to 0 °C. Stirring was continued for 30 min at 0–5 °C, and the mixture was worked up to yield 7.05 g of a yellow oil, which was distilled under reduced pressure.

This distillation gave 1.06 g (19%) of a mixture of **8** and **9**: bp 39–42 °C (1 mmHg) n^{18}_D 1.4694; IR (CCl_4) 1644, 1540, 1383; ^1H NMR (100 MHz, CCl_4) 2.51 (m, 4 H, CH_2 protons of **8**), 2.97 (m, 4 H, CH_2 protons of **9**), 5.09 (tt, 1 H, $J_1 = J_2 = 4.6$ Hz, $J_3 = J_4 = 7.5$ Hz, $HCNO_2$ of **9**), 5.39 (m, 1 H, $HCNO_2$ of **8**), 5.62 (s, 2 H, HC=CH of **9**), 5.91 (m, 2 H, HC=CH of **8**). Anal. Calcd for $C_5H_7NO_2$: C, 53.10; H, 6.19; N, 12.39. Found: C, 52.75; H, 6.42; N, 12.51. Reported for **8** and **9**: lit.[6g] bp 37–38 °C (0.08 mmHg); lit.[6c] bp 41.5 °C (2 mmHg); n^{20}_D 1.4681.

Column chromatography (silica gel, hexane:ethyl acetate = 4:1) of the residue (5.67 g) gave three fractions.

(i) 0.63 g (8%) of **12**, R_f 0.58. Purification by distillation gave 0.47 g of **12**: bp 103–105 °C (2–3 mmHg); n^{17}_D 1.4834; IR (CCl_4) 1647 (ONO_2), 1558 (NO_2), 1439, 1371 (NO_2); ^{13}C NMR 83.91 (CNO_2), 84.36 ($CONO_2$); ^1H NMR (360 MHz, CCl_4) 2.2–2.35 (m, 4 H, CH_2 protons), 2.39 (m, 1 H), 2.80 (dq, 1 H), 5.01 (m, 1 H, W = 19.8 Hz,

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(37) The stereochemistry predicted by such processes is presently being examined using cyclohexene-*3,3,6,6-d*$_4$ as substrate. See, e.g.: Wolfe, S.; Campbell, P. G. C. *J. Am. Chem. Soc.* **1971**, *93*, 1497–1499.
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(42) Olah, G. A.; Spear, R. J.; Hiberty, P. C.; Hehre, W. J. *J. Am. Chem. Soc.* **1976**, *98*, 7470–7475.

$HCNO_2$), 5.52 (m, 1 H, W = 16.5 Hz, $HCONO_2$). Anal. Calcd for $C_5H_8N_2O_5$: C, 34.10; H, 4.58; N, 15.90. Found: C, 33.94; H, 4.67; N, 16.24.

(ii) 1.9 g (22%) of a mixture of **10** and **13** (ratio 3:1 based on ^{13}C NMR). Rechromatography of this mixture gave 0.025 g of **13** and 1.42 g of **10**. Compound **10**: R_f 0.37; bp 98–101 °C (3–4 mmHg); IR (CCl_4) 1739 (C=O), 1545 (NO_2), 1429, 1365 (NO_2); ^1H NMR (100 MHz, CCl_4) 1.97 (s, 3 H, CH_3COO), 2.0–2.4 (m, 5 H, CH_2 protons), 2.66 (dt, 1 H, J_1 = 5.5 Hz, J_2 = 15.5 Hz, $AcOCCHCNO_2$); ^{13}C NMR 75.10 (COAc), 85.20 (CNO_2). Anal. Calcd for $C_7H_{11}NO_4$: C, 48.55; H, 6.40; N, 8.09. Found: C, 48.71; H, 6.52; N, 8.31. Compound **13** was identified by its spectra and transformation to the nitro cyclopentanol **15**: ^1H NMR (100 MHz, CCl_4) 1.9–2.5 (m, 6 H, CH_2 protons), 2.02 (s, 3 H, CH_3COO), 4.92 (m, 1 H, $HCNO_2$), 5.65 (m, 1 H, HCOAc); ^{13}C NMR (CCl_4) 90.04 (CNO_2), 77.93 (COAc).

(iii) 2.34 g (26%) of **11**, R_f 0.30. Distillation afforded 2.07 g of pure material: bp 85 °C (0.1 mmHg); n^{20}_D 1.4636; IR (CCl_4) 1749, 1560, 1432, 1373; ^1H NMR (360 MHz, CCl_4) 2.00 (m, 5 H, CH_3COO and CH_2), 2.25 (sextet, 1 H), 2.47 (dq, 1 H, J_1 = 6.1 Hz, J_2 = 8.4 Hz, J_3 = 15.5 Hz), 2.55 (m, 3 H, CH_2 protons), 4.86 (m, 1 H, W = 25.4 Hz, $HCNO_2$), 5.12 (m, 1 H, W = 18.8 Hz, HCOAc); ^{13}C NMR 74.61 (COAc), 84.77 (CNO_2). Anal. Calcd for $C_7H_{11}NO_4$: C, 48.55; H, 6.40; N, 8.09. Found: C, 48.63; H, 6.47; N, 8.27.

Hydrolysis of the Nitro Acetates to Nitro Alcohols. H_2SO_4 (0.5 mL) was added to methanol (15 mL) containing 0.7 g of a mixture of **10** and **13**, and the reaction mixture was stirred for 20 h. After the usual workup, column chromatography of the residue (SiO_2, 5/40 μm, hexane:ethyl acetate 1:1) gave 0.39 g of **14** and **15** (ratio 4:1): ^{13}C NMR 72.19 (COH of **14**), 85.36 (CNO_2 of **14**), 73.54 (COH of **15**), 96.40 (CNO_2 of **15**). Further chromatography of the mixture gave pure **14**: IR (C_6H_6) 3580, 3450 (br), 2940, 1530, 1365; ^1H NMR (100 MHz, $CHCl_3$) 1.7–2.5 (m, 6 H, CH_2 protons), 2.73 (s, 1 H, OH), 4.57 (m, 1 H, W = 16.0 Hz, H-COH), 5.12 (m, 1 H, W = 21.2 Hz, $HCNO_2$). Analogous treatment of **11** gave 0.31 g of a nitro alcohol: IR (C_6H_6) 3575, 3400 (br), 2940, 1530, 1370; ^1H NMR (100 MHz, C_6H_6) 1.35–2.4 (m, 6 H, CH_2 protons), 3.16 (s, 1 H, OH), 4.00 (m, 1 H, W = 18.0 Hz, HCOH), 4.32 (septet, 1 H, W = 26.0 Hz, $HCNO_2$).

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Registry No. 1, 88157-56-6; **2a**, 88157-57-7; **2b**, 88157-58-8; **4**, 6925-08-2; **6**, 4883-68-5; **7**, 65283-37-6; **8**, 7053-55-6; **9**, 6925-11-7; **10**, 88157-60-2; **11**, 88157-61-3; **12**, 88157-59-9; **13**, 6925-12-8; **14**, 88157-73-7; **15**, 88157-72-6; **16**, 88157-65-7; **17**, 88157-64-6; **18**, 88157-63-5; **19**, 88157-62-4; **20**, 88157-66-8; **21**, 88157-67-9; **22**, 88157-68-0; **23**, 88157-69-1; **24**, 4734-90-1; **25**, 88157-70-4; **26**, 88157-71-5; **27**, 65283-41-2; **28**, 65283-40-1; $AcONO_2$, 591-09-3; NO_2^+, 14522-82-8; methylenecyclobutane, 1120-56-5; cyclopentene, 142-29-0; cyclohexene, 110-83-8; cyclooctene, 931-88-4; norbornene, 498-66-8.

Supplementary Material Available: Details of the structural assignments to compounds **4** and **6–24** and full experimental details of the reactions of cyclohexene, cyclooctene, methylenecyclobutane, and norbornene (11 pages). Ordering information is given on any current masthead page.

1,3-Asymmetric Induction: Highly Stereoselective Synthesis of 2,4-Trans-Disubstituted γ-Butyrolactones and γ-Butyrothiolactones

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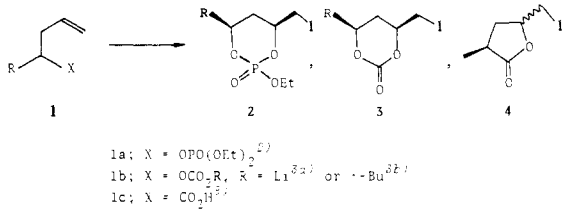
Abstract: A novel 1,3-trans asymmetric induction has been observed for the halolactonization of α- and α,β-substituted γ,δ-unsaturated amides. The 1,3-trans selectivity is lost in the threo diastereomers of amides with a β-OH or β-OAc substituent, due to the 1,2-cis directing ability of these substituents.

Macrolides and ionophores have prompted interest in the development of methods for the control of stereochemistry in acyclic systems.[2] Compared with the extensive work for the 1,2-asymmetric induction, the principal method being, for example, aldol condensation, variations of Claisen rearrangement, and epoxidation of unsaturated alcohols, the work for the remote asymmetric induction is relatively rare. In both 1,2- and remote asymmetric inductions, most of the methodologies seem to rely on a six-membered chairlike transition state, through which a high degree of asymmetry has been induced by virtue of a propensity of the largest numbers of substituents to take the equatorial positions. For example, a high 1,3-asymmetric induction has been observed for the iodocyclization of homoallylic phosphates **1a**[3] and carbonates **1b**,[4] providing 1,3-cis disubstituted cyclic phosphate **2** and carbonates **3**, respectively. For the reactions involving a five-membered cyclic transition state, the number of examples being limited, the 1,3-cis selectivity seems to be general.[5]



In this paper we describe the first and very novel example of a 1,3-trans asymmetric induction in the halolactonization of

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(2) For an excellent review on this subject, see: Bartlett, P. A. *Tetrahedron* **1980**, *36*, 2.
(3) Bartlett, P. A.; Jernstedt, K. K. *J. Am. Chem. Soc.* **1977**, *99*, 4829.
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