J|A|C|S
ARTICLES
Published on Web 01/03/2002

Interplay of Orbital Symmetry and Nonstatistical Dynamics in the Thermal Rearrangements of Bicyclo[*n*.1.0]polyenes

Mayra B. Reyes, Emil B. Lobkovsky, and Barry K. Carpenter*

Contribution from the Department of Chemistry and Chemical Biology, Baker Laboratory, Cornell University, Ithaca, New York 14853-1301

Received September 14, 2001

Abstract: CASSCF and CASPT2 calculations have been carried out on some of the thermal rearrangements of bicyclo[2.1.0]pentene (**BCP)**, bicyclo[4.1.0]hepta-2,4-diene (**BCH**), bicyclo[6.1.0]nona-2,4,6-triene (**BCN**), and 9,9-dicyanobicyclo[6.1.0]nona-2,4,6-triene (**DCBCN**). In addition, experiments have been conducted to determine the stereoselectivity and temperature dependence of the nondegenerate rearrangement of 9,9-dicyanobicyclo[6.1.0]nona-2,4,6-triene-*exo*-^{15}N. The calculations and experiments allow a consistent picture to be drawn for these reactions. The principal conclusions are as follows. (1) The ring-walk rearrangements of **BCP**, **BCN**, and **DCBCN** are pericyclic reactions occurring with a strong preference for inversion of configuration at the migrating carbon. However, the ring-walk rearrangement of **BCH** is a nonpericyclic reaction. (2) The rearrangement of **DCBCN** to 9,9-dicyanobicyclo[4.2.1]nona-2,4,7-triene occurs with a preferred stereochemistry corresponding to a 1,3 migration with retention. However, this reaction is not a pericyclic process; the stereoselectivity is probably of dynamic origin. (3) Cyano substituents can significantly reduce the activation energy for a reaction occurring via a singlet biradical, but they do not necessarily cause the intermediate to sit in a deeper local minimum on the potential energy surface.

Introduction

Theoretical and experimental work from this laboratory has led to the conclusion that the formal [1,*n*] sigmatropic migrations of carbon will usually not be pericyclic processes, and that the stereochemistry of such reactions will consequently not be subject to the rules of orbital symmetry conservation.[1] Instead, these reactions are expected to occur with the intervention of transient singlet-state biradicals, whose behavior is frequently not well described by statistical kinetic models such as transition state theory (TST).[2] Calculations on the nominal [1,3] rearrangement of bicyclo[3.2.0]hept-2-ene[3] and on the vinylcyclopropane rearrangement[4] provide supporting examples for the general proposal.

The simple physical picture that leads to this generalization also allows ready identification of situations where exceptions may occur. The thesis is merely that the overlap of the orbitals in the transition structure for a [1,*n*] migration of carbon is usually too weak to permit the significant "aromatic" delocalization associated with a thermally allowed pericyclic process. However, one could certainly conceive of constrained transition-state geometries where good pericyclic overlap for a [1,*n*] migration should be possible. The number of such exceptions is not expected to be large; in fact, only two are readily apparent. The first has been previously discussed:[3a] the [1,5] sigmatropic migration in 1,3-cyclopentadienes.[5] Because this reaction is really only a 1,2 rearrangement, and because the thermally allowed reaction should occur with retention of configuration at the migrating atom, it is easy to attain a pericyclic transition structure with strong overlap among the orbitals of the making and breaking bonds. In accord with this picture is the known very high stereoselectivity of the reaction[5] and the fact that the experimental activation enthalpy[6] plus the estimated heat of formation for the reactant in the spiro[4.4]nona-1,3-diene rearrangement place the transition structure roughly 20 kcal/mol below that calculated for a mechanism involving a singlet biradical.[3a]

The second potential exception could occur for the "ring-walk" rearrangements[7] of those bicyclo[*n*.1.0]polyenes for which the thermally allowed process should occur with *inversion* at the migrating carbon. The first two members of the series are the [1,3] shift in bicyclo[2.1.0]pentene[8] and the [1,7] shift in bicyclo[6.1.0]nona-2,4,6-triene.[9] In this class of reaction, ready

(1) Newman-Evans, R. H.; Simon, R. J.; Carpenter, B. K. *J. Org. Chem.* **1990**, *55*, 695−711.
(2) (a) Carpenter, B. K. *Acc. Chem. Res.* **1992**, *25*, 520−528. (b) Carpenter, B. K. *Angew. Chem., Int. Ed.* **1998**, *37*, 3340−3350.
(3) (a) Carpenter, B. K. *J. Am. Chem. Soc.* **1995**, *117*, 6336−6344. (b) Carpenter, B. K. *J. Am. Chem. Soc.* **1996**, *118*, 10329−10330. (c) Beno, B. R.; Wilsey, S.; Houk, K. N. *J. Am. Chem. Soc.* **1999**, *121*, 4816−4826. (d) Wilsey, S.; Houk, K. N.; Zewail, A. H. *J. Am. Chem. Soc.* **1999**, *121*, 5772−5786.
(4) (a) Davidson, E. R.; Gajewski, J. J. *J. Am. Chem. Soc.* **1997**, *119*, 10543−10544. (b) Houk, K. N.; Nendel, M.; Wiest, O.; Storer, J. W. *J. Am. Chem. Soc.* **1997**, *119*, 10545−10546. (c) Doubleday, C.; Nendel, M.; Houk, K. N.; Thweatt, D.; Page, M. *J. Am. Chem. Soc.* **1999**, *121*, 4720−4721. (d) Doubleday, C. *J. Phys. Chem. A* **2001**, *105*, 6333−6341.
(5) Boersma, M. A. M.; De Haan, J. W.; Kloosterziel, H.; Van de Ven, L. J. M. *J. Chem. Soc. D* **1970**, 1168−1169.
(6) (a) Dane, L. M.; De Haan, J. W.; Kloosterziel, H. *Tetrahedron Lett.* **1970**, 2755−2758. (b) Semmelhack, M. F.; Weller, H. N.; Foos, J. S. *J. Am. Chem. Soc.* **1977**, *99*, 292−294. (c) Replogle, K. S.; Carpenter, B. K. *J. Am. Chem. Soc.* **1984**, *106*, 5751−5753.
(7) (a) Woodward, R. B.; Hoffmann, R. *The Conservation of Orbital Symmetry*; Verlag Chemie: Weinheim, 1970. (b) Klärner, F.-G. *Top. Stereochem.* **1984**, *15*, 1−42.

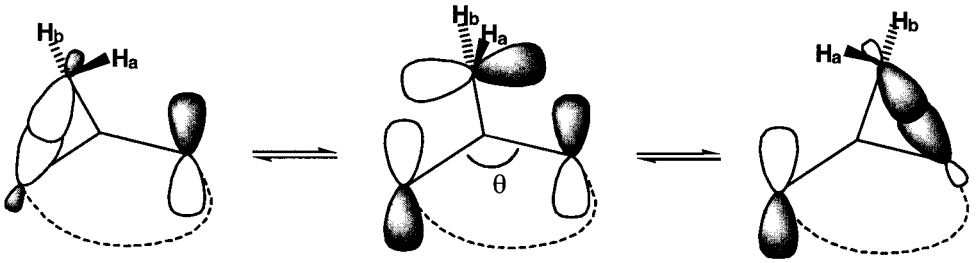


Figure 1. Schematic representation of a "ring-walk" reaction occurring with inversion of configuration at the migrating carbon.

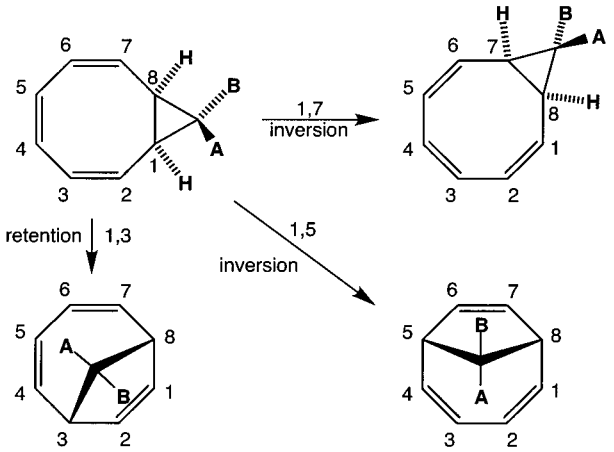
access to a pericyclic transition state seems possible because the cyclopropane ring opening is expected to be accompanied by a rehybridization at the migrating carbon and a more-or-less "automatic" completion of the pericyclic array. The situation is depicted schematically in Figure 1.

One might anticipate that a pericyclic transition structure would be especially favored if the angle θ were small, bringing the p_π orbitals at the ends of the conjugated chain into better overlap with the p-type orbital on the migrating carbon. A small value of θ implies a small ring and hence a short conjugated chain of π orbitals.

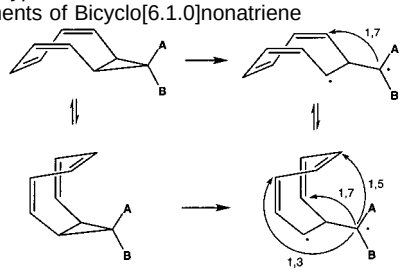
A second factor favoring a short conjugated chain can be discerned if one views the pericyclic transition structure from the perspective of a perturbation theory model. Interaction of the p-type orbital on the migrating carbon with the nonbonding π molecular orbital (NBMO) of the chain should be most favorable when the coefficients of the NBMO at the termini of the chain are largest. This will necessarily be the case for the shortest chain, since the NBMO has to be "shared" by more carbons as the chain lengthens. It seems reasonable to anticipate, therefore, that the ring-walk rearrangement in bicyclo[2.1.0]-pentene would be the most likely candidate for a pericyclic mechanism in this class of [1,*n*] carbon migrations.

However, the second member of the series—the 1,7 ring-walk in bicyclo[6.1.0]nonatrienes—is in some ways more interesting because it is accompanied by another nominal sigmatropic rearrangement that is either a 1,3 or a 1,5 shift (or both).[10] Studies on substituted molecules have shown that the ring-walk occurs with very high stereochemical fidelity for the "allowed" inversion of configuration.[9] The competing 1,3/1,5 rearrangement occurs with lower stereoselectivity and favors the stereochemistry that would be retention for a 1,3 migration or inversion for a 1,5 migration (see Scheme 1)—i.e., the "forbidden" stereochemistry from an orbital symmetry conservation standpoint. The 1,3/1,5 shift also appears to have a higher barrier than the ring-walk since in similarly substituted molecules it occurs at a reasonable rate only at about 180 °C, whereas the ring-walk occurs at about 100 °C.[9,10] The computational and experimental results reported in the present paper are designed to distinguish among several mechanisms that could be invoked to explain these facts. The mechanisms under consideration are as follows:

Scheme 1. Summary of Possible Rearrangements of Bicyclo[6.1.0]nonatriene, with the Products Selected Being Those Corresponding to the Observed Stereochemical Preference



Scheme 2. Hypothetical Biradical Mechanism for the Rearrangements of Bicyclo[6.1.0]nonatriene



(A) The ring-walk and the skeletal rearrangements are both pericyclic sigmatropic reactions, with the minor product of the [1,3]/[1,5] migration coming from a nominally allowed [1,3]-inversion and/or [1,5]-retention pathway.

(B) The ring-walk is a purely pericyclic reaction, but the competing rearrangement occurs by parallel pericyclic and biradical mechanisms, with the biradical giving both stereoisomers of the bicyclo[4.2.1]nonatriene product.

(C) The ring-walk is a purely pericyclic reaction, but the competing rearrangement is a purely biradical process.

(D) Both the ring-walk and the competing rearrangement occur by biradical mechanisms. To explain the markedly different rates of the two rearrangements, this mechanism would appear to require two ancillary hypotheses: that the exo and endo conformers of the reactant be separated by a barrier higher than that for C−C bond scission, and that the putative biradicals obtained from the exo and endo conformers of the reactant be distinct and separated from interconversion by a barrier higher than any of those for product formation (see Scheme 2).

Mechanisms C and D can be considered to have subcatogories in which the reactions occurring via singlet biradicals have stereochemical outcomes determined either by conformational

(8) (a) Schoeller, W. W. *J. Am. Chem. Soc.* **1975**, *97*, 1978−1980. (b) Klärner, F. G.; Adamsky, F. *Angew. Chem.* **1979**, *91*, 738−739. (c) Klärner, F. G.; Adamsky, F. *Chem. Ber.* **1983**, *116*, 299−322. (d) Klärner, F. G.; Glock, V.; Figge, H. *Chem. Ber.* **1986**, *119*, 794−812. (e) Skancke, P. N.; Yamashita, K.; Morokuma, K. *J. Am. Chem. Soc.* **1987**, *109*, 4157−4162. (f) Jensen, F. *J. Am. Chem. Soc.* **1989**, *111*, 4643−4647.
(9) (a) Klärner, F. G. *Angew. Chem., Int. Ed. Engl.* **1972**, *11*, 832−833. (b) Klärner, F. G.; Wette, M. *Chem. Ber.* **1978**, *111*, 282−298.
(10) Klärner, F. G. *Tetrahedron Lett.* **1971**, 3611−3614.

barriers on the potential energy surface or by nonstatistical reaction dynamics.[2]

The relationship of these issues to the general proposal described in the opening paragraph is that mechanisms A and B invoke pericyclic [1,3] and/or [1,5] shifts of carbon that would constitute clear counter examples to the general thesis, since they belong to neither of the classes for which exceptions are anticipated.

We have approached the resolution of the mechanistic questions by joint application of ab initio electronic structure theory and experiment. Calculations have been performed on the ring-walk reactions of bicyclo[2.1.0]pentene, bicyclo[4.1.0]-hexadiene, and bicyclo[6.1.0]nonatriene, as well as on the 9,9-dicyano derivative of the last molecule. In addition, the rearrangements of the parent and 9,9-dicyanobicyclo[6.1.0]-nonatrienes to the corresponding bicyclo[4.2.1]nonatrienes have been explored computationally. Experiments were carried out on a 9,9-dicyanobicyclo[6.1.0]nonatriene that was stereoselectively ^{15}N-labeled in one of the nitrile substituents.

Results

CASPT2 Calculations on the Ring-Walk Reaction in the Parent Hydrocarbons. CASPT2/6-31G(d)//CASSCF/6-31G-(d) calculations were carried out on the transition states and any intermediates for the ring-walk reactions of bicylo[2.1.0]-pentene, bicyclo[4.1.0]hepta-2,4-diene, and bicylo[6.1.0]octa-2,4,6-triene. In each case, the C_s-symmetry stationary points corresponding to the inversion and retention stereochemistries were located at the CASSCF level, using (4,4), (6,6), and (8,8) active spaces respectively for the three different reactants. The nature of the stationary point was determined by harmonic normal-mode analysis at the same level. Single-point CASPT calculations from the CASSCF references were then performed to allow for dynamic electron correlation corrections to the relative energies.

If all three molecules underwent allowed pericyclic ring-walk reactions, one would expect the allowed-stereochemistry stationary points (inversion for the first and third molecules, but retention for the second) all to be transition structures and all to be lower in energy than their forbidden-stereochemistry counterparts. However, this relative-energy criterion is not sufficient to show that the reactions are pericyclic in nature. The reason is that molecular symmetries permitting the correct pericyclic topolgy for "aromatic" stabilization are also those for which biradical and zwitterion configurations would be permitted to mix in a nonpericyclic intermediate or transition structure. Specifically, in the C_s point group the closed-shell (zwitterionic) configurations are obviously of A' symmetry for all three molecular systems. The open-shell (biradical) configurations are also of A' symmetry in the "allowed" geometry but are of A'' symmetry in the "forbidden" geometry. Thus, a lower energy for the "allowed" structure might be due only to the fact that more electronic configurations can mix in that geometry. To determine whether pericyclic overlap plays a significant role, one needs to analyze some measure of bonding of the migrating carbon to the migration origin (or, equivalently by symmetry, to the migration terminus) in the transition structure. We chose for that purpose the Wiberg bond index,[11] calculated in the natural atomic orbital basis.[12] The results are summarized in Table 1, but their analysis is deferred to the Discussion section of this paper.

Table 1. Summary of CASPT2//CASSCF Results on the Ring-Walk Reactions

n^a	$\Delta H_{ret}^{\ddagger} - \Delta H_{inv}^{\ddagger}$ (kcal/mol)^b	ΔWBI^c
4	11.1	0.1435
6	0.09	−0.0173
8	6.3	0.0910

[a] Index defining the size of the larger ring in the reactant (n), the number of active electrons and orbitals in the MCSCF calculations (n,n), and the order of the sigmatropic rearrangement constituting the ring-walk ([1,n − 1]). [b] Difference in CASPT2(n,n)//CASSCF(n,n) activation enthalpies for the ring-walk with retention and inversion of configuration. All calculations used the 6-31G(d) basis set and unscaled CASSCF vibrational frequencies. [c] Difference in the Wiberg bond index between the inversion and retention transition structures, where the bond in question is the one made (or equivalently the one broken) in the ring-walk reaction.

CASPT2 and CASSCF Calculations on the Bicyclo[6.1.0]-nonatriene-to-Bicyclo[4.2.1]nonatriene Rearrangement. CASSCF(8,8)/6-31G(d) calculations revealed the existence of several biradical-like stationary points on the bicyclo[6.1.0]/bicyclo-[4.2.1]nonatriene potential energy surface (PES). Their connections to each other and to the closed-shell minima were revealed by intrinsic reaction coordinate (IRC) analyses. This connectivity pattern is summarized in Schemes 3 and 4. Energies of the stationary points were refined at the CASPT2(8,8)/6-31G(d) level. The presence of at least one valley ridge inflection (VRI) point[13] on the PES was inferred, for reasons presented in the Discussion section.

Because the experiments described below were carried out on 9,9-dicyanobicyclo[6.1.0]nonatriene, and because computational studies on related systems have suggested significant influence from such substituents,[14] it seemed desirable to undertake additional calculations on this substituted compound. However, the substitution not only increases the number of heavy atoms by four, but it also increases the size of the minimal active space from (8,8), corresponding to 1764 singlet-coupled configuration state functions (CSFs), to (12,12), corresponding to 226 512 singlet CSFs. It was consequently not feasible to carry out as detailed a survey of the substituted PES as had been attempted for the parent hydrocarbon. Neither CASSCF vibrational frequency nor single-point CASPT2 calculations proved to be computationally tractable.

Several studies on reactions involving singlet biradicals have used unrestricted density functional theory (DFT) or hybrid Hartree−Fock/DFT models.[3c,15] Such approaches would be computationally feasible for the present study, but we were aware that they were controversial.[16] We consequently elected

(11) Wiberg, K. B. *Tetrahedron* **1968**, *24*, 1083−1096.

(12) Reed, A. E.; Weinstock, R. B.; Weinhold, F. *J. Chem. Phys.* **1985**, *83*, 735−746.

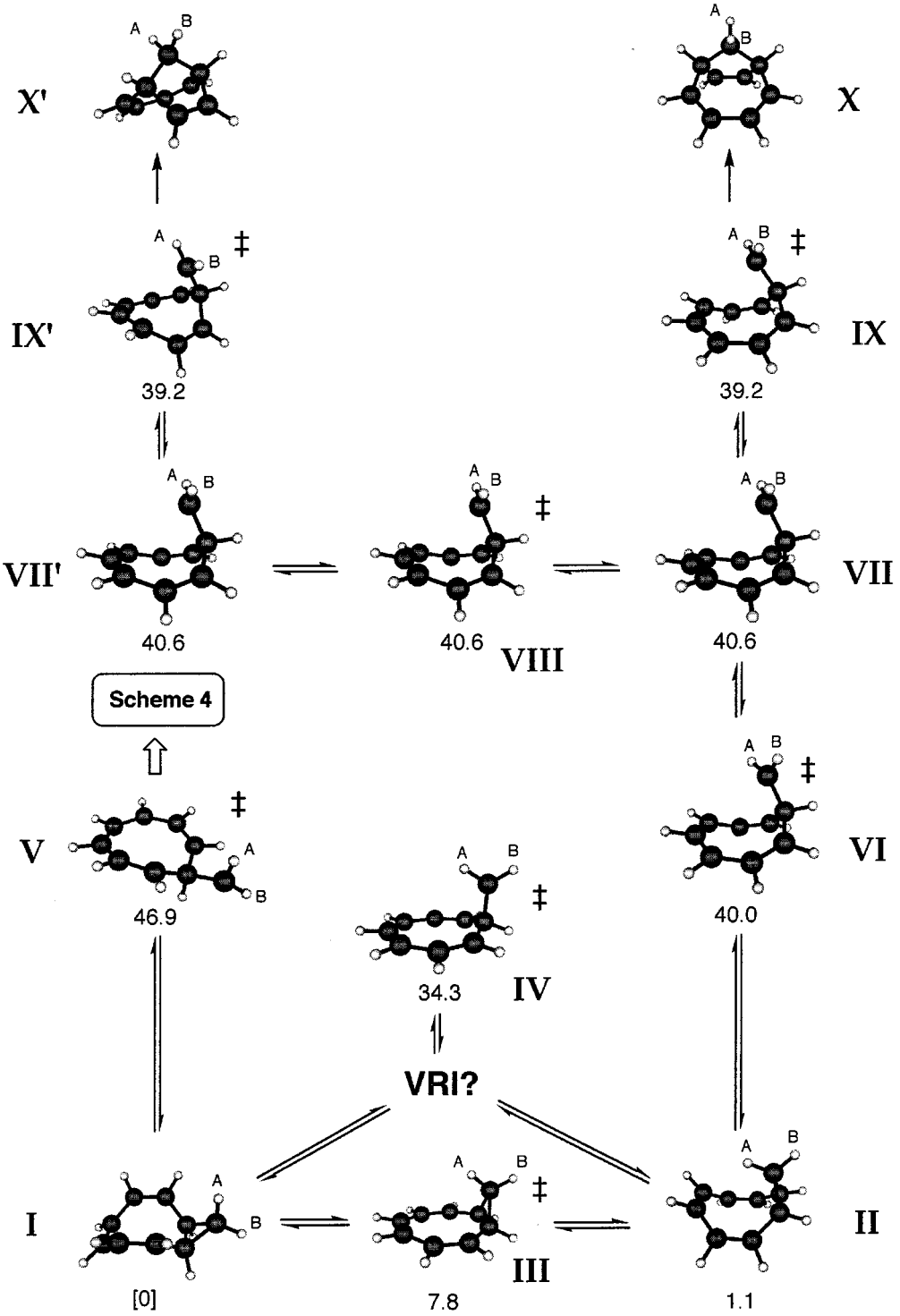
(13) (a) Valtazanos, P.; Ruedenberg, K. *Theor. Chim. Acta* **1986**, *69*, 281−307. (b) Taketsugu, T.; Tajima, N.; Hirao, K. *J. Chem. Phys.* **1996**, *105*, 1933−1939. (c) Ramquet, M.-N.; Dive, G.; Dehareng, D. *J. Chem. Phys.* **2000**, *112*, 4923−4934.

(14) Kless, A.; Nendel, M.; Wilsey, S.; Houk, K. N. *J. Am. Chem. Soc.* **1999**, *121*, 4524−4525.

(15) See, for example: (a) Goldstein, E.; Beno, B.; Houk, K. N. *J. Am. Chem. Soc.* **1996**, *118*, 6036−6043. (b) Houk, K. N.; Beno, B. R.; Nendel, M.; Black, K.; Yoo, H. Y.; Wilsey, S.; Lee, J. *THEOCHEM* **1997**, *398*−*399*, 169−179. (c) Cramer, C. J. *J. Am. Chem. Soc.* **1998**, *120*, 6261−6269.

(16) (a) Yamaguchi, K.; Jensen, F.; Dorigo, A.; Houk, K. N. *Chem. Phys. Lett.* **1988**, *149*, 537−542. (b) Wittbrodt, J. M.; Schlegel, H. B. *J. Chem. Phys.* **1996**, *105*, 6574−6577. (c) Staroverov, V. N.; Davidson, E. R. *J. Am. Chem. Soc.* **2000**, *122*, 186−187. (d) Orlova, G.; Goddard, J. D. *J. Chem. Phys.* **2000**, *112*, 10085−10094. (e) Grafenstein, J.; Cremer, D. *Mol. Phys.* **2001**, *99*, 981−989.

Scheme 3. CASPT2(8,8)//CASSCF(8,8)/6-31G(d) Structures and Relative Enthalpies (kcal/mol) for the Rearrangement of *cis*-Bicyclo[6.1.0]nona-2,4,6-triene[a]

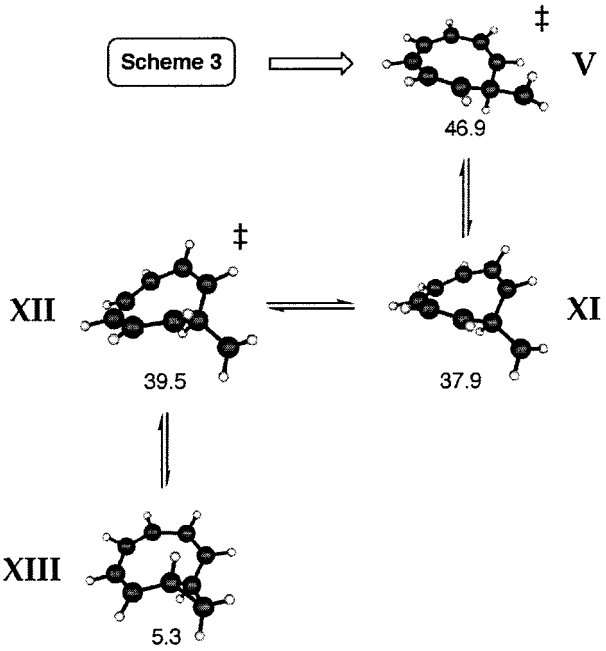


[a] VRI is a valley ridge inflection point.

to restrict our attention to CASSCF(12,12) calculations on key stationary points. The results are summarized in Scheme 5.

Since vibrational frequency calculations were not feasible for the cyano-substituted species, the identity of each stationary point and its connections to the others on the PES were identified by analogy with the results from the calculations on the parent hydrocarbon. In most cases the structures were very similar, and so this comparison was straightforward. The single exception was the C_s-symmetry structure **XIX**. In the unsubstituted hydrocarbon the analogous structure, **VIII**, was found to be a transition state at the CASSCF level (before inclusion of ZPE differences). The calculations on **XIX** suggest that it is probably an intermediate, since geometry optimization without symmetry restriction did not cause it to relax to a lower-energy C_1 structure. However, this difference is probably inconsequential since the ZPE and CASPT2 corrections removed the shallow local minima on the PES for the parent system and would very probably do the same for the PES of the cyano-substituted molecule.

Scheme 4. CASPT2(8,8)//CASSCF(8,8)/6-31G(d) Structures and Relative Enthalpies for the Rearrangement of *trans*-Bicyclo[6.1.0]nona-2,4,6-triene



For reasons described in the Discussion section, we also carried out CASPT2(6,6) calculations on singlet 1,1-dicyanotrimethylene biradical and its conrotatory transition state for formation from 1,1-dicyanocyclopropane. These results are summarized in Table 2.

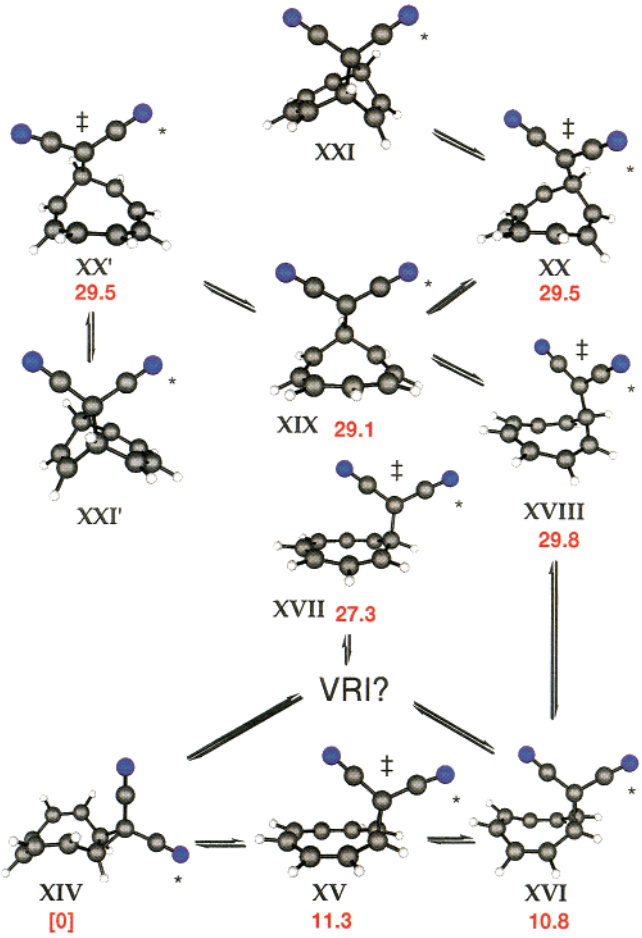
Synthesis and Rearrangement of 9,9-Dicyanobicyclo[6.1.0]-nonatriene-*exo*-^{15}N. It has been recognized for some time that for the parent *cis*-bicyclo[6.1.0]nona-2,4,6-triene the most facile thermal rearrangement is an electrocyclic reaction that involves breaking the C1−C8 bond.[17] Scission of the C1−C9 bond, required for both the ring-walk rearrangement and the skeletal rearrangement to bicyclo[4.2.1]nona-2,4,7-triene, is apparently unable to compete to any significant extent. However, the situation changes if appropriate substituents are attached to C9. Groups that can weaken the C1−C9 bond while strengthening the C1−C8 bond are known to be capable of reversing the relative favorability of cleavage of these two bonds.[9,10]

We sought to take advantage of this substituent effect in the design of a compound that could provide some mechanistic insight into the formation of the bicyclo[4.2.1]nonatriene isomer. In particular, we were interested in applying the criterion of temperature dependence of stereoselectivity, which has proven useful in elucidating the mechanisms of other rearrangements.[18] The idea behind this approach is that reactions occurring by parallel mechanisms are expected to exhibit temperature-dependent kinetic product ratios, since the heats of formation of the competitive transition structures will be different except by improbable coincidence. However, reactions whose stereochemical outcome is determined by nonstatistical dynamics have thus far been found to exhibit little or no temperature dependence of their product ratios, provided that the products differ only in absolute configuration or in the position of a kinetically innocent isotopic label.[4d,18b,19] This last condition is necessary because products that are diastereomeric to the extent of more than an isotope difference are likely to be formed in temperature-dependent ratios by almost any mechanism.

Bearing in mind these criteria, we elected to prepare a 9,9-dicyanobicyclo[6.1.0]nonatriene that was ^{15}N-labeled in just one

(17) Vogel, E. *Angew. Chem., Int. Ed. Engl.* **1963**, *2*, 1−11.
(18) (a) Newman-Evans, R. H.; Carpenter, B. K. *J. Am. Chem. Soc.* **1984**, *106*, 7994−7995. (b) Lyons, B. A.; Pfeifer, J.; Carpenter, B. K. *J. Am. Chem. Soc.* **1991**, *113*, 9006−9007.

Scheme 5. CASSCF(12,12)/6-31G(d) Structures and Relative Potential Energies for the Ring-Walk and Skeletal Rearrangements of 9,9-Dicyanobicyclo[6.1.0]nona-2,4,6-triene[a]



[a] By analogy with the calculations on the unsubstituted hydrocarbon, structure **XVII** is expected to be the ring-walk transition state. The asterisk shows the location of the ^{15}N label in the experiments conducted on this system. The structure **XXI** corresponds to the preferred product found in these experiments.

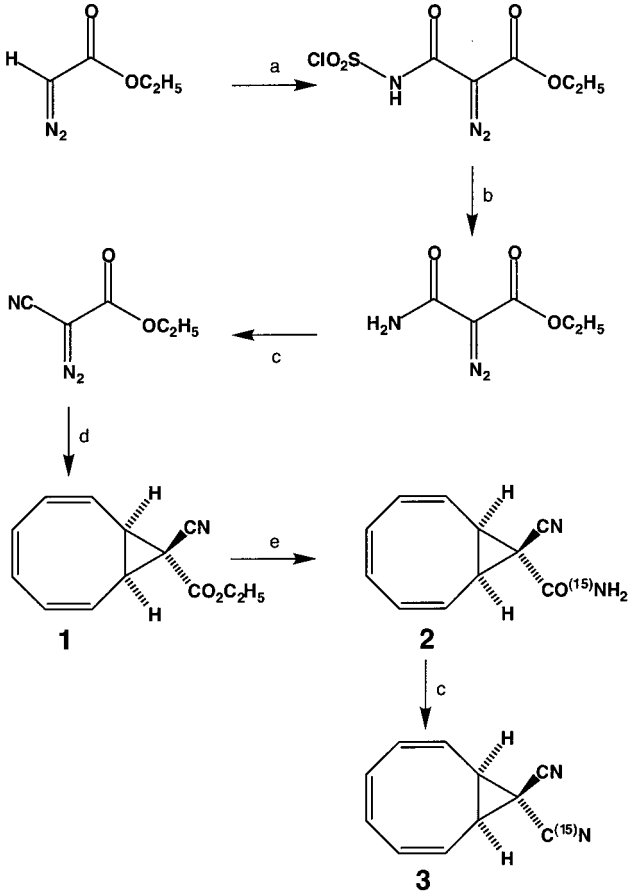
Table 2. Summary of Calculations on Trimethylene and 1,1-Dicyanotrimethylene

structure	CASSCF energy[a]	CASPT2 energy[a]	ZPE[b]	E_{rel}[c]
cyclopropane	−117.0754726110	−117.4628191820	54.443	−59.1
conrotatory TS	−116.9903067925	−117.3610644412	49.099	−0.69
trimethylene	−116.9903428141	−117.3606419232	49.474	[0]
1,1-dicyano cyclopropane	−300.5731417157	−301.4806041218	54.025	−44.1
conrotatory TS (dicyano)	−300.5177969213	−301.4021522091	48.376	−0.52
1,1-dicyano-trimethylene	−300.5184540962	−301.4021193831	48.871	[0]

[a] Absolute energies in hartree. [b] Unscaled harmonic zero-point energies in kcal/mol. [c] Relative enthalpies at 0 K. The first three entries use trimethylene as the reference; the last three use 1,1-dicyanotrimethylene as the reference. All species are in their lowest singlet electronic states.

(19) Lyons, B. A.; Pfeifer, J.; Peterson, T. H.; Carpenter, B. K. *J. Am. Chem. Soc.* **1993**, *115*, 2427−2437.

Scheme 6. Synthetic Procedure for the Preparation of 9,9-Dicyanobicyclo[6.1.0]nona-2,4,6-triene-*exo*-^{15}N [a]



[a] The reagents and conditions for each step were as follows: (a) ClO_2S-NCO, Et_2O, −70 °C; (b) H_2O, EtOH, room temperature; (c) Cl_3CCOCl, Et_3N, CH_2Cl_2, 0−5 °C; (d) cyclooctatetraene, $[Rh(OAc)_2]_2$ (catalyst), CCl_4, room temperature; (e) $^{15}NH_3$, H_2O, EtOH, room temperature.

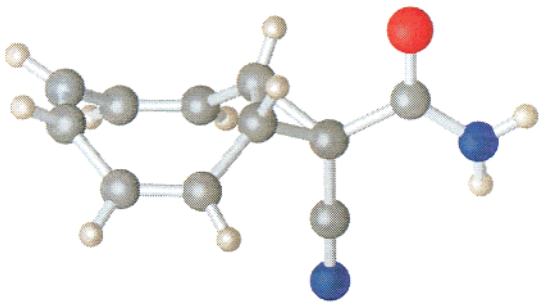


Figure 2. Structure of compound **2** determined by X-ray crystallography.

of the nitriles. The synthetic sequence that permitted this is shown in Scheme 6. The stereochemistry of the cyclopropanation reaction was established by obtaining single-crystal X-ray diffraction data on the unlabeled version of amide **2**. The molecular structure deduced from this experiment is shown in Figure 2.

Thermal rearrangement of compound **3** to bicyclo[4.2.1]-nonatrienes **4x** and **4n** occurred cleanly at 120−170 °C. ^{15}N NMR revealed that the products were formed in a 2.7:1 ratio but did not reveal which was which. To determine that information, compound **1** was heated to 200 °C, causing it to rearrange to a mixture of stereoisomeric bicyclo[4.2.1]nonatrienes **5x** and **5n** (Scheme 7). Surprisingly, treatment of this product

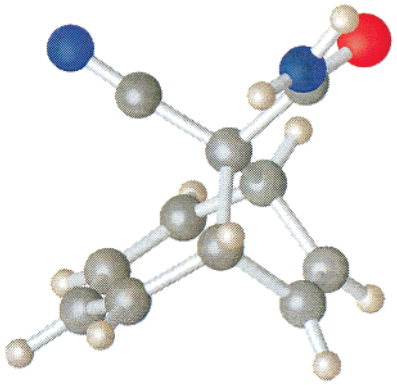
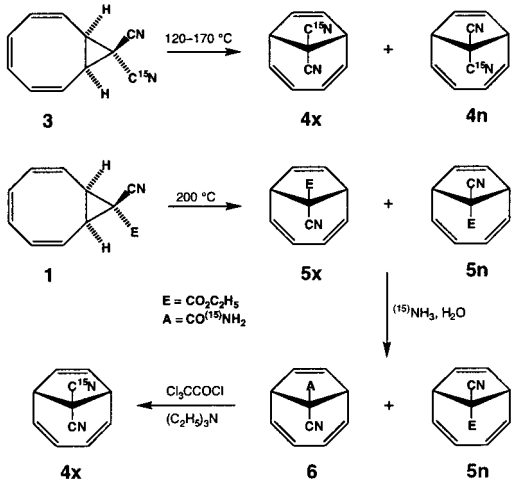


Figure 3. Structure of compound **6** determined by X-ray crystallography.

Scheme 7. Summary of the Thermal Rearrangement and the Procedure Used To Deduce Its Stereochemical Preference



mixture with aqueous ammonia caused only one of the components to be converted to an amide, while the other remained unaffected. The amide was isolated and recrystallized, and an X-ray diffraction structure was determined. It is shown in Figure 3. Replacement of the normal ammonia in this last reaction by $^{15}NH_3$, followed by dehydration of the resulting amide, permitted selective generation of compound **4x**, thereby allowing the preferred stereochemistry of the rearrangement to be deduced. In accord with earlier studies on unsymmetrically substituted bicyclo[6.1.0]nonatrienes,[10] the rearrangement to the bicyclo[4.2.1]nonatriene skeleton was found to occur with a preference for the stereochemistry that would correspond to retention in a 1,3 migration and/or inversion in a 1,5 migration.

The stereoselectivity of the rearrangement of compound **3** was determined as a function of temperature and reaction medium, with results that are summarized in Tables 3 and 4.

Discussion

Calculations on the Ring-Walk Rearrangements. The results summarized in Table 1 show evidence at the CASPT2//CASSCF level of theory for pericyclic transition structures of the ring-walk reactions with inversion of configuration for both bicyclo[2.1.0]pentene and bicyclo[6.1.0]nonatriene. The significant enthalpy difference between inversion and retention transition structures, in combination with the substantially greater Wiberg bond indices for the former stereochemistry, lead us to this conclusion. As anticipated, the magnitude of pericyclic

Table 3. Temperature Dependence of the Product Ratio in Benzene Solution

temperature (±0.2 °C)	product ratio (**4x**/**4n**)
120.0	2.64
130.0	2.61
140.0	2.62
150.0	2.65
160.0	2.72
170.0	2.70

Table 4. Solvent Dependence of the Product Ratio, **4x**/**4n**, at 160 °C

benzene-d_0	benzene-d_6	*cis*-decalin	*trans*-decalin
2.82	2.78	3.29	3.49
2.79	2.79	3.22	3.44
2.79	2.81	3.35	3.39
2.80	2.84	3.15	3.50
2.79	2.79		
2.80 ± 0.02	2.80 ± 0.03	3.25 ± 0.16	3.46 ± 0.09

overlap is greater in the transition structure for the rearrangement of the smaller bicyclic molecule. In fact, at the CASSCF(4,4)/6-31G(d) level there is even a shallow minimum in the PES for the C_s-symmetry geometry corresponding to the ring-walk "transition structure" with inversion. If this reflected the true PES, the reaction might be considered pericylic but not concerted! However, ZPE and CASPT2 corrections remove the minimum and restore a more traditional description of the reaction as a concerted, pericyclic process.

The story is very different for the ring-walk reaction in bicyclo[4.1.0]hexadiene (norcaradiene). In this case the allowed pericyclic process should occur with retention of configuration. However, we find virtually no difference between the energies or Wiberg bond indices of the retention and inversion structures. It appears that the retention of stereochemistry mandated by orbital symmetry conservation leads to a transition structure in which overlap is too poor to permit the completion of a pericyclic array. This ring-walk reaction is thus calculated to occur by a nonpericyclic biradical mechanism. Previous studies have come to the same conclusion and have discussed its rationalization with the experimental stereoselectivity.[14,20]

Before leaving the analysis of the ring-walk reactions, it is perhaps worth noting that the bicyclo[6.1.0]nonatriene version probably involves a valley ridge inflection point on the PES. The calculated geometry for the transition structure reveals an almost perfectly flat eight-membered ring, suggesting that both exo and endo conformations of the reactant undergo the degenerate rearrangement via the same transition state. This would be possible only if there existed a VRI between the stereoisomeric reactants and the transition structure. IRC analysis in mass-weighted coordinates showed the transition state to be connected only to the endo reactant, but it is known that IRC calculations cannot reveal the existence of a VRI, since all common IRC algorithms force selection of one of the two paths when they encounter such a bifurcation point.[21] In support of the existence of a VRI is the unusual energy profile along the IRC, shown in Figure 4. The "elbow" in the IRC profile, occurring at an energy just below that found for the ring-inversion transition structure, is strongly suggestive of the presence of a VRI.

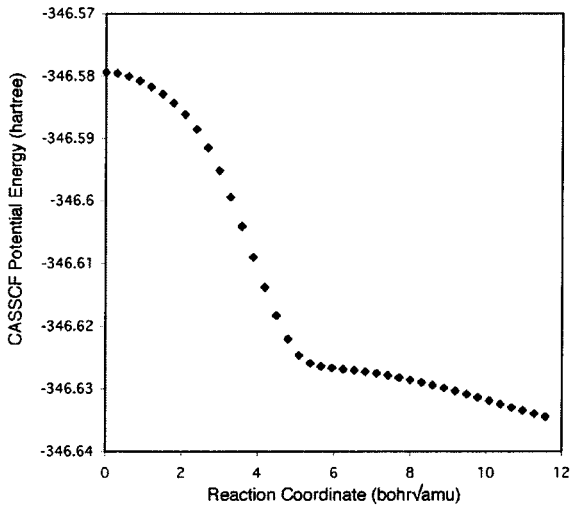


Figure 4. CASSCF(8,8)/6-31G(d) potential energy profile along the IRC from the ring-walk transition structure of bicyclo[6.1.0]nona-2,4,6-triene.

Calculations on the Bicyclo[6.1.0]nonatriene-to-Bicyclo-[4.2.1]nonatriene Rearrangement. We have chosen to analyze the computational results for this reaction in terms of the mechanistic hypotheses labeled A−D in the Introduction. We begin with the CASPT2//CASSCF calculations on the parent hydrocarbon.

For the calculations to be consistent with mechanism A or B, at least some component of the bicyclo[6.1.0]nonatriene-to-bicyclo[4.2.1]nonatriene rearrangement would have to occur by a pericyclic mechanism. However, the calculations offered no support for such a pathway. The only pericyclic transition structure that could be found on the entire PES was that for the ring-walk reaction, **IV**. Three other ring-opening transition structures were located (**V**, **VI**, and **XII**), but in each case they connected a stereoisomer of bicyclo[6.1.0]nonatriene to a singlet biradical.

Mechanism D was found to be inconsistent with the computational results on several grounds. First, as described above, was the fact that the ring-walk transition structure **IV** showed clear indications of being pericyclic. Actually, two additional nonpericyclic mechanisms (**II** → **VI** → **VII** → **VIII** → **VII′** →**VI′** → **II′** and **I** → **V** → **XI** → **V′** → **I′**) for the ring-walk reaction *were* found, but they were calculated to be substantially higher in activation enthalpy than the pericyclic process. Second was the fact that, while discrete exo and endo conformers of the biradical were located, as mechanism D had posited, formation of the exo biradical was calculated to have a *higher* barrier by nearly 7 kcal/mol than formation of the endo one. Third was the computational result that the barrier to interconversion of conformers **I** and **II** was much lower than the barrier to any ring-opening reaction.

Mechanism C was found to be the most consistent with the calculations. Within this mechanism, the original analysis of the problem considered two possible explanations for the stereochemical preference observed experimentally. One was that there were conformational barriers on the biradical PES, and the other was that the singlet biradical may be subject to nonstatistical dynamical effects of the kind proposed in several other reactions. At least in the case of the parent hydrocarbon,

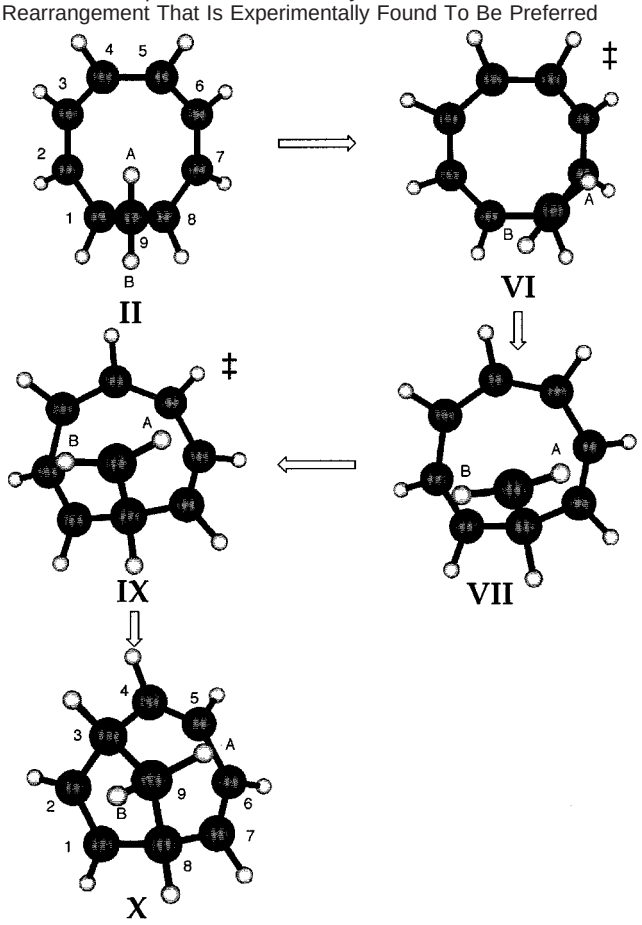
(20) Jarzecki, A. A.; Gajewski, J. J.; Davidson, E. R. *J. Am. Chem. Soc.* **1999**, *121*, 6928−6935.
(21) Yanai, T.; Taketsugu, T.; Hirao, K. *J. Chem. Phys.* **1997**, *107*, 1137−1146.

the calculations offered no support at all for the former explanation. As has been found in several other reactions, the PES in the vicinity of the singlet biradical structures was calculated to be extremely flat. At the CASSCF level, structure **VII** was found to be a very shallow minimum, with potential energy barriers of 0.08 kcal/mol for reclosure to **II** and 0.27 kcal/mol for closure to the product. The barrier to interconversion of enantiomers **VII** and **VII′** via C_s-symmetry TS **VIII** was found to be less than 0.01 kcal/mol. With ZPE, thermal, and CASPT2 corrections, the minimum corresponding to structure **VII** disappeared completely. The reaction is best described at this level of theory as involving ring opening onto an energetic plateau from which barrierless exits lead to both bicyclo[6.1.0]- and bicyclo[4.2.1]nonatrienes. For such reactions, we have argued previously that the selection of exits may be determined largely by the phenomenon of dynamic matching.[3a,22] In effect, this hypothesis says that the biradical has the highest probability of leaving the plateau by the exit that it encounters first. The order of encounter of exits is determined by the detailed trajectories that biradicals follow across the PES, and those, in turn, owe their behavior in large measure to the dynamics of *formation* of the biradical. A complete computational test of such a hypothesis requires a full molecular dynamics simulation, but the results of the electronic structure calculations reported here at least lend a measure of plausibility to the idea.

The first thing to notice about the stereochemical issue is that the calculations show a strong preference for *retention* of configuration at the migrating carbon. The lack of complete stereoselectivity in the formation of bicyclo[4.2.1]nonatriene is due to a competition between 1,3 and 1,5 migrations with retention, not to a competition between rearrangements with retention and inversion of configuration. All attempts to find a transition structure for internal rotation in biradical **VII** resulted only in collapse to the pericyclic transition structure **VI**. Thus, according to the calculations, the formation of bicyclo[4.2.1]-nonatriene occurs with retention at the migrating carbon not because there is a large barrier to internal rotation in the biradical intermediate, but instead because those biradicals undergoing internal rotation find themselves simply returning to the bicyclo-[6.1.0]nonatriene minimum.

The sequence of stationary points **II** → **VI** → **VII** → **IX** → **X** defines a path that corresponds to the experimentally preferred stereochemistry of the rearrangement (at least in substituted analogues.) However, it is important to recognize that there is calculated to be no additional barrier preventing a molecule from following the alternative path **II** → **VI** → **VII** → **VIII** → **VII′** → **IX′** → **X′**, which would give the minor stereoisomer of the product if the groups on the migrating carbon were made distinguishable. We believe that the preference for the former path derives from the fact that it is dynamically coherent. As shown in the top view (Scheme 8), the conversion of **II** to the ring-opening transition structure **VI** involves substantial clockwise rotation about the C8−C9 bond. This motion orients the migrating methylene in such a fashion that the first product-forming transition state to be encountered is the one corresponding to a 1,3 migration with retention. This is precisely the phenomenon that we have referred to as dynamic matching.[3a]

Scheme 8. Top View of the Pathway for the Skeletal Rearrangement That Is Experimentally Found To Be Preferred

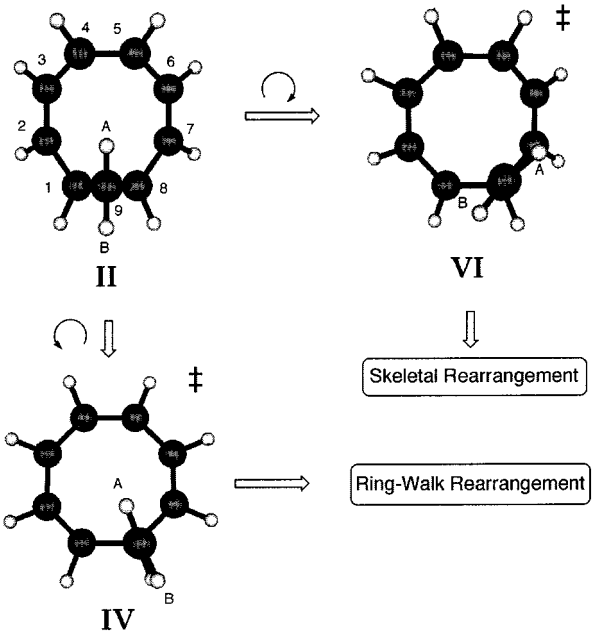


However, this explanation requires further scrutiny. We have previously suggested that the generally observed preference for *inversion* at the migrating carbon in a 1,3 migration is explicable in terms of dynamic matching.[3a] How, then, could the preference for retention observed in this case have the same origin? We believe that the answer is an interesting one having to do with the competitive ring-walk process. The issue is really the sense of rotation that accompanies the initial bond cleavage. The situation is summarized in Scheme 9, which compares the transition structures for the skeletal rearrangement and the pericyclic ring-walk reaction, using the same top view employed for Scheme 8. While the former reaction, as noted, involves clockwise rotation about the C8−C9 bond, the latter clearly entails counterclockwise rotation in order to achieve the overlap that closes the pericyclic array. In the absence of the ring-walk reaction, previously presented arguments[3a] suggest that the preferred mode of bond cleavage for the 1,3 shift would have involved counterclockwise rotation, leading eventually to product formation with predominant inversion of configuration. However, the presence of the ring-walk pathway causes trajectories that involve breaking the C1−C9 bond with counterclockwise torsion about C8−C9 to be diverted from the skeletal rearrangement into the lower-energy ring-walk manifold. To avoid this "trap", the initial bond scission has to occur with the less favorable clockwise internal rotation, which then leads to the 1,3 shift occurring with preferential retention.

Although not directly relevant to the questions addressed in this study, we note in passing that *trans*-bicyclo[6.1.0]nonatriene, **XIII**, is calculated to be capable of undergoing a degenerate

(22) Hrovat, D. A.; Fang, S.; Borden, W. T.; Carpenter, B. K. *J. Am. Chem. Soc.* **1998**, *120*, 5603−5604.

Scheme 9. Comparison of the Sense of Internal Rotation about the C1−C9 Bond That Accompanies the Ring-Walk or Skeletal Rearrangement



ring-walk reaction that would be nonpericyclic, i.e., unlike the ring-walk in the cis stereoisomer (see Scheme 4). This computational result seems to be consistent with conclusions derived from experiments on the trans isomer.[23]

In the case of the norcaradiene ring-walk reaction, it has been suggested that substituents on the migrating carbon can significantly change the shape of the PES.[14] Since the experimental studies in the bicyclo[6.1.0]nonatriene series *required* substituents on the migrating carbon, we felt it necessary to address the possibility that the analysis presented above for the parent hydrocarbon might not be relevant for the system that was studied experimentally. Of particular concern was the known radical-stabilizing ability of nitriles. Experiments suggest that a pair of geminal nitriles should provide 12.4 ± 0.9 kcal/mol of radical stabilization.[24] If these substituents similarly stabilized *bi*radicals, one might anticipate that the very flat region of the PES found for the bicyclo[6.1.0]nonatriene-to-bicyclo[4.2.1]-nonatriene rearrangement in the parent hydrocarbon would be transformed in the dicyano derivative to a surface with distinct local minima and barriers to reaction that might control the observed stereochemistry. However, the actual results were quite different from this simple picture. As summarized in Scheme 5, the addition of the nitriles did substantially reduce the barriers for the ring-walk and skeletal rearrangements of bicyclo[6.1.0]-nonatriene but did *not* cause the appearance of substantial PES minima corresponding to singlet biradical intermediates.

To find out whether this result was peculiar to the bicyclononatriene system, we also carried out CASPT2(6,6) calculations on the singlet biradical generated from C1−C2 scission in 1,1-dicyanocyclopropane. Here, too, the calculations showed that the substituents should cause a 15 kcal/mol reduction in the barrier to ring opening without generating a significant minimum on the PES for the resulting singlet biradical (see Table 2). Only the conrotatory transition structure was investigated, since this is found to be the one of lowest energy for the stereomutation of unsubstituted cyclopropane.[25]

A simple interpretation of the computational results on the substituent effect is the following. The formation of a singlet biradical from a closed-shell reactant is generally a reaction that is highly endothermic and hence, by the Hammond postulate, should have a very "late" or biradical-like transition state. Introduction of radical-stabilizing substituents does lead to a reduction in the overall endothermicity of the reaction, but the effect of the substituents is quantitatively similar on the biradical and the transition state. The result is reduction in the barrier to bond cleavage without a qualitative change in the topography of the PES.

The qualitative similarity of the PES for the substituted and unsubstituted bicyclo[6.1.0]nonatrienes leads us to conclude that the mechanisms of the rearrangements in both systems should also be similar. In particular, the bicyclo[6.1.0]nonatriene-to-bicyclo[4.2.1]nonatriene rearrangements for both systems are expected to be nonpericyclic and to occur with a dynamically determined preference for the 1,3-migration with retention of configuration.

Experimental Studies on the Rearrangement of 9,9-Dicyanobicyclo[6.1.0]nonatriene-*exo*-^{15}N. The experimentally determined stereochemical preference for the rearrangement of 9,9-dicyanobicyclo[6.1.0]nonatriene to 9,9-dicyanobicyclo[4.2.1]-nonatriene is in accord with both the calculations and earlier experimental studies on unsymmetrically substituted analogues. There is no doubt that the observed preference for the product corresponding to a 1,3 shift with retention (or, indistinguishably, a 1,5 shift with inversion) is kinetic rather than thermodynamic in origin, since the products differ only in the position of nitrogen isotopes, and so would have an equilibrium constant very close to unity. If the kinetic preference arose from the existence of parallel mechanisms occurring over potential energy barriers of different heights, one would expect to see a temperature-dependent product ratio. However, within the experimental error, the product ratio is found to be temperature independent over a range of 50 °C.[26] The lack of temperature dependence, and the dependence on reaction medium, are in accord with experimental results that we have found for other reactions in which the product ratio is believed to be determined by the dynamic behavior of a transient intermediate.[18] That is consequently the explanation that we favor for the present results, too.

The quantitative stereoselectivity observed in this rearrangement (73−77%, depending on reaction medium) is similar to that found for the corresponding reaction of the 9-cyano-9-methyl analogues (85% for the endo isomer and 70% for the exo).[9,10] However, without a detailed theoretical study of the 9-cyano-9-methyl compounds, it is unclear whether this similarity is mechanistically significant.

(23) Glock, V.; Wette, M.; Klärner, F. G. *Tetrahedron Lett.* **1985**, *26*, 1441−1444.
(24) Pakusch, J.; Beckhaus, H. D.; Rüchardt, C. *Chem. Ber.* **1991**, *124*, 1191−1198.
(25) (a) Getty, S. J.; Davidson, E. R.; Borden, W. T. *J. Am. Chem. Soc.* **1992**, *114*, 2085−2093. (b) Baldwin, J. E.; Yamaguchi, Y.; Schaefer, H. F., III. *J. Phys. Chem.* **1994**, *98*, 7513−7522. (c) Doubleday, C., Jr. *J. Phys. Chem.* **1996**, *100*, 3520−3526. (d) Baldwin, J. E.; Freedman, T. B.; Yamaguchi, Y.; Schaefer, H. F., III. *J. Am. Chem. Soc.* **1996**, *118*, 10934−10935.
(26) The discrepancy between the uncertainty deduced from the replicate measurements at constant temperature (Table 3) and the single-point measurements at varying temperature (Table 2) suggests that the experiments must have been subject to a small systematic error. Even when this is included, there is still no signficant temperature dependence detectable.

Experimental Section

Computational Details. GAMESS[27] was used for most of the CASSCF calculations, although analytical vibrational frequency and Wiberg bond index calculations were carried out with Gaussian 98.[28] CASPT2 calculations were carried out with MOLCAS.[29] All calculations used the 6-31G(d) basis set with six Cartesian *d* functions.

Calculations were carried out on a 500 MHz dual-processor Compaq Alpha DS-20E workstation, or a Dell Precision 330 workstation employing a 1.7 GHz Pentium 4 processor and running the Linux operating system.

Ethyl α-(Chlorosulfonylaminocarbonyl)diazoacetate. To a solution of ethyl diazoacetate (5.0 g, 43.8 mmol) in ether (50 mL) that was stirred under nitrogen at −70 °C (dry ice/acetone bath) was added a solution of chlorosulfonyl isocyanate (6.2 g, 43.8 mmol) in ether (20 mL) over a 30 min period. After the addition was complete, the reaction was stirred at the same temperature for an additional 3 h. The reaction mixture was warmed to room temperature, and the ether was removed using a rotary evaporator. No further purification was required, and the product was obtained in 95% yield (11.1 g). ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.39 (t, $J = 7$ Hz, 3H), 4.39 (q, $J = 7$ Hz, 2H), 11.32 (bs, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 63.51, 157.39, 163.33.

Ethyl α-(Aminocabonyl)diazoacetate. A solution of ethyl α-(chlorosulfonylaminocabonyl)diazoacetate (9.23 g 36.25 mmol) in ethanol (50 mL) and water (5 mL) was allowed to stand overnight at room temperature. The solvent was decanted from the precipitate that formed, and the solid was washed with ether. The ether was decanted, and traces were removed under vacuum. This gave the product (4.33 g, 76%) as yellow crystals. ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.33 (t, $J = 7$ Hz, 3 H), 4.31 (q, $J = 7$ Hz, 2H), 5.76 (bs, 1H), 7.58 (bs, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 14.25, 61.78, 163.36, 163.67.

Ethyl α-Cyanodiazoacetate. A mixture of ethyl α-(aminocabonyl)-diazoacetate (1.47 g, 9.35 mmol) and triethylamine (3.12 g, 28.05 mmol) in dichloromethane (20 mL) was cooled in an ice bath and stirred while a solution of trichloroacetyl chloride (5.61 g, 30.86 mmol) in dry CH_2Cl_2 (20 mL) was added dropwise at a rate to maintain the temperature between 0 and 5 °C. After the addition was finished, the solution was treated sequentially with water and aqueous sodium bicarbonate. The separated organic layer was dried over magnesium sulfate, and the solvent was removed using a rotary evaporator. The crude product was purified by chromatography on silca gel, utilizing 30% ethyl acetate in hexane as eluent. Pure ethyl α-cyanodiazoacetate (0.72 g, 69%) was obtained as a yellow oil. IR (neat): 2229, 2131, 1714 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.34 (t, $J = 7$ Hz, 3H), 4.35 (q, $J = 7$ Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 14.21, 63.42, 107.30, 161.17.

9-Cyanobicyclo[6.1.0]nona-2,4,6-triene-9-carboxylic Acid Ethyl Ester, 1. A 50 mL round-bottomed flask was charged with rhodium acetate dimer (2 mol %) in carbon tetrachloride (15 mL). Cyclooctatetraene (0.96 g, 9.18 mmol) was added, and the mixture was stirred at room temperature while ethyl α-cyanodiazoacetate (1.02 g, 9.18 mmol) was added dropwise. The solution became warm but required no external cooling if the addition was done slowly. After the addition, the reaction mixture was stirred until no starting material could be detected by TLC. The reaction mixture was then filtered, and the solvent was removed under vacuum. The crude product was purified by chromatography on silica gel utilizing 30% ethyl acetate in hexane as eluent. Pure product (0.43 g, 22%) was obtained as a very thick yellowish oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.35 (t, $J = 7$ Hz, 3H), 2.64 (s, 2H), 4.28 (q, $J = 7$ Hz, 2H), 5.94 (d, $J = 11$ Hz, 4H), 6.17(d, $J = 11$ Hz, 2H). ^{13}C NMR(100 MHz, $CDCl_3$): δ 14.04, 26.86, 35.16, 62.91, 115.65, 122.39, 125.98, 132.30, 167.20.

9-Cyanobicyclo[6.1.0]nona-2,4,6-triene-9-carboxamide, 2. To a solution of 9-cyanobicyclo[2.2.l]nona-2,4,6-triene-9-carboxylic acid ethyl ester (0.33 g, 1.53 mmol) in ethanol (3 mL) was added aqueous ammonia (5 mL, 3.3 N solution). For preparation of the ^{15}N-labeled amide, ^{15}N-labeled aqueous ammonia (99 at. %, 3.3 N solution) was used. The reaction mixture was stirred for several days until no starting material was observed by GC in a quenched aliquot. When the reaction was complete, the solvent was removed and the resulting solid washed with ether several times. The ether was decanted, and the solid was dried under vacuum. No further purification was needed. 9-Cyanobicyclo-[2.2.l]nona-2,4,6-triene-9-carboxamide was obtained in 53% yield. ^{1}H NMR (200 MHz, DMSO): δ 2.97 (s, 2H), 4.5 1 (s, 1H), 6.39 (d, $J = 10$ Hz, 2H), 6.42 (s, 2H), 6.64 (d, $J = 10$ Hz, 2H). ^{13}C NMR (75 MHz, DMSO): δ 28.19, 32.40, 117.04, 123.51, 125.68, 131.10, 166.13.

The stereochemistry of the product was determined by X-ray crystallography. Details of the diffraction experiment and the structure are provided in the Supporting Information. The diffraction data were obtained on a colorless monoclinic single crystal of dimensions 0.6 × 0.4 × 0.1 mm^3. The crystal was mounted on a Bruker diffractometer equipped with a CCD detector, using Mo Kα radiation at 0.71073 Å and operating at 293 K. The structure was solved in space group $P2_1/c$, with $a = 15.675(3)$ Å, $b = 8.651(2)$ Å, $c = 7.1630(14)$ Å, $\beta = 99.38(3)°$, $V = 958.3(3)$ Å^3, $Z = 4$, $D = 1.291$ g cm^{-3}, and $\mu = 0.085$ mm^{-1}. A total of 4080 reflections were collected in the range $1.32 \leq 2\theta \leq 23.28°$, leading to a set of 1364 independent reflections. The structure was solved by direct methods using full-matrix least-squares on F^2. All non-hydrogen atoms were refined with anisotropic thermal parameters. The refinement, using 168 parameters, converged to $R(F) = 0.0588$, $R_w(F) = 0.1357$, and GOF = 1.032.

9,9-Dicyanobicyclo[6.1.0]nona-2,4,6-triene, 3. To a stirred mixture of 9-cyanobicyclo[2.2.l]nona-2,4,6-triene-9-carboxamide (0.10, 0.54 mmol) and dry triethylamine (0.108 g, 1.08 mmol) in CH_2Cl_2 (5 mL) was added a solution of trichloroacetyl chloride (0.108 g, 0.54 mmol) in dry CH_2Cl_2 (5 mL) dropwise between 0 and 5 °C. After the addition was finished, the mixture was treated sequentially with water and aqueous sodium bicarbonate. The separated organic solution was dried over magnesium sulfate, and the solvent was removed using a rotary evaporator. No further purification was needed (40 mg, 44%). ^{1}H NMR (200 MHz, $CDCl_3$): δ 2.73 (s, 2H), 5.98 (d, $J = 10.0$ Hz, 2H), 6.00 (s, 2H), 6.26 (d, $J = 10.0$ Hz, 2H). ^{13}C NMR(100 MHz, $CDCl_3$): δ 11.20, 34.95, 112.89, 115.89, 121.45, 126.06, 132.91 ppm.

9,9-Dicyanobicyclo[4.2.1]nona-2,4,7-triene, 4x and 4n. A solution of 9,9-dicyanobicyclo[6.1.0]nona-2,4,6-triene (20 mg) in benzene-d_6 was placed in a 16.5 cm × 5 mm i.d. Pyrex tube. The solution was degassed by three freeze−pump−thaw cycles and sealed under vacuum. The tube was heated to a constant temperature in the range 120−170 °C in a thermostated oil bath. The tube was cooled quickly to room temperature, opened, and the contents were transferred to a NMR tube. The products were analyzed by ^{1}H NMR. In the case of the ^{15}N-labeled reactant, the ratio of product stereoisomers was determined by their ^{15}N NMR shifts at 4.86 and 8.93 ppm downfield from 9,9-dicyanobicyclo-[6.l.0]nonatriene-*exo*-^{15}N used as reference at 0 ppm. ^{1}H NMR (400 MHz, $CDCl_3$): δ 2.85 (d, $J = 3.8$ Hz, 2H), 4.52 (s, 2H), 5.28 (m, 2H),

(27) GAMESS (Version 26 OCT 2000 R4 for UNIX): Schmidt, M. W.; Baldridge, K. K.; Boatz, J. A.; Elbert, S. T.; Gordon, M. S.; Jensen, J. H.; Koseki, S.; Matsunaga, N.; Nguyen, K. A.; Su, S. J.; Windus, T. L. *J. Comput. Chem.* **1993**, *14*, 1347−1363.

(28) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Zakrzewski, V. G.; Montgomery, J. A., Jr.; Stratmann, R. E.; Burant, J. C.; Dapprich, S.; Millam, J. M.; Daniels, A. D.; Kudin, K. N.; Strain, M. C.; Farkas, O.; Tomasi, J.; Barone V.; Cossi, M.; Cammi, R.; Mennucci, B.; Pomelli, C.; Adamo, C.; Clifford, S.; Ochterski, J.; Petersson, G. A.; Ayala, P. Y.; Cui Q.; Morokuma, K.; Malick, D. K.; Rabuck, A. D.; Raghavachari, K.; Foresman, J. B.; Cioslowski, J.; Ortiz J. V.; Baboul, A. G.; Stefanov, B. B.; Liu G.; Liashenko, A.; Piskorz, P.; Komaromi, I.; Gomperts, R.; Martin, R. L.; Fox, D. J.; Keith, T.; Al-Laham, M. A.; Peng, C. Y.; Nanayakkara, A.; Gonzalez, C.; Challacombe, M.; Gill, P. M. W.; Johnson, B.; Chen, W.; Wong, M. W.; Andres, J. L.; Gonzalez C.; Head-Gordon, M.; Replogle, E. S.; Pople, J. A. *Gaussian 98*, Rev. A.9; Gaussian, Inc.: Pittsburgh, PA, 1998.

(29) Andersson, K.; Barysz, M.; Bernhardsson, A.; Blomberg, M. R. A.; Cooper, D. L.; Fleig, T.; Fülscher, M. P.; de Graaf, C.; Hess, B. A.; Karlström, G.; Lindh, R.; Malmqvist, P.-Å.; Neogrády, P.; Olsen, J.; Roos, B. O.; Sadlej, A. J.; Schütz, M.; Schimmelpfennig, B.; Seijo, L.; Serrano-Andrés, L.; Siegbahn, P. E. M.; Stålring, J.; Thorsteinsson, T.; Veryazov; V.; Widmark, P.-O. *MOLCAS*, Version 5; Lund University, Sweden, 2000.

5.72 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 35.50, 52.61, 114.02, 117.67, 120.54, 127.65, 130.77.

9-Cyanobicyclo[4.2.1]nona-2,4,7-triene-9-carboxylic Acid Ethyl Ester, 5x and 5n. A solution of 9-cyanobicyclo[6.1.0]nona-2,4,6-triene-9-carboxylic acid ethyl ester (20 mg) in C_6D_6 was placed in a 16.5 cm × 5 mm i.d. Pyrex tube. The solution was degassed by three freeze−pump−thaw cycles and sealed under vacuum. The tube was heated to 200 °C in a thermostated oil bath for 24 h. The tube was cooled to room temperature, opened, and the contents were used in the next reaction.

9-Cyanobicyclo[4.2.1]nona-2,4,7-triene-9-carboxylic acid amide, 6. To a solution of 9-cyanobicyclo[4.2.l]nona-2,4,7-triene-9-carboxylic acid ethyl ester (0.100 g, 0.47 mmol) in ethanol (3 mL) was added aqueous ammonia (3 mL, 3 N solution in water). For preparation of the ^{15}N-labeled amide, ^{15}N-labeled aqueous ammonia (99 at. %, 3.3 N solution) was used. The reaction mixture was then stirred until no starting material in a quench aliquot was observed by GC (only one isomer reacted, and the reaction took several days). When the reaction was complete, the solvent was removed, and the solid residue was washed with ether several times to remove the ester that had not reacted. The ether was decanted, and the solid was dried under vacuum. The crude product was recrystallized from cold THF/pentane. ^{1}H NMR (400 MHz, $CDCl_3$): δ 3.77 (d, J = 4.0 Hz, 2H), 5.26 (d, J = 2.0 Hz, 2H), 5.51 (br s, 2H), 6.21 (m, 4H).

The stereochemistry of the product was determined by X-ray crystallography. Details of the diffraction experiment and the structure are provided in the Supporting Information. Single crystals of the compound were obtained as a mono-THF solvate. The diffraction data were obtained on a colorless triclinic single crystal of dimensions 0.4 × 0.4 × 0.05 mm^3. The crystal was mounted on a Bruker diffractometer equipped with a CCD detector, using Mo Kα radiation at 0.71073 Å and operating at 293 K. The structure was solved in space group $P\bar{1}$, with a = 6.3516(6) Å, b = 10.3942(10) Å, c = 10.7314(10) Å, α = 94.2070(17)°, β = 96.9300(13)°, γ = 102.4230(16)°,V = 683.23(11) Å^3, Z = 2, D = 1.256 g cm^{-3}, and μ = 0.084 mm^{-1}. A total of 3417 reflections were collected in the range $1.92 \le 2\theta \le 24.71°$, leading to a set of 2267 independent reflections. The structure was solved by direct methods using full-matrix least-squares on F^2. All non-hydrogen atoms were refined with anisotropic thermal parameters. The refinement, using 213 parameters, converged to $R(F)$ = 0.0697, $Rw(F)$ = 0.1449, and GOF = 0.617.

9,9-Dicyanobicyclo[4.2.1]nona-2,4,7-triene-*exo*-^{15}N, 4x. To a stirred mixture of compound **6** (50 mg, 0.27 mmol) and dry triethylamine (0.54 g, 0.54 mmol) in CH_2Cl_2 at 0−5 °C was added a solution of trichloroacetyl chloride (0.05 1 g, 0.27 mmol) in dry CH_2Cl_2 dropwise. After the addition was finished, the mixture was treated with water and a saturated solution of sodium bicarbonate (5 × 15 mL). The separated organic solution was dried with magnesium sulfate, and the solvent was removed using a rotary evaporator. The crude mixture was placed in an NMR tube, and a ^{15}N NMR was recorded. ^{1}H NMR (200 MHz, C_6D_6): δ 2.85 (d, J = 3.8 Hz, 2H), 4.52 (s, 2H), 5.28 (m 2H), 5.72 (m 2H). ^{15}N NMR (40.5 MHz, C_6D_6): 4.86 ppm downfield from 9,9-dicyanobicyclo[6.l.0]nonatriene-*exo*-^{15}*N* used as reference at 0.

Conclusion

The calculations and experiments reported in this paper appear to provide a consistent picture. The conclusions from the study can be summarized as follows.

(1) The ring-walk reaction in the bicyclo[*n*.1.0]polyenes studied is a pericyclic reaction when the orbital-symmetry-allowed stereochemistry is inversion at the migrating carbon but nonpericyclic when the orbital-symmetry-allowed stereochemistry is retention.

(2) The degree of pericyclic overlap in ring-walk reactions occurring with inversion decreases as the size of the ring containing the conjugate π system increases.

(3) The bicyclo[6.1.0]nonatriene-to-bicyclo[4.2.1]nonatriene rearrangement is a nonpericyclic process both for the hypothetical reaction of the unsubstituted hydrocarbon and for the actual reaction of the 9,9-dicyano derivative. This is in accord with the general principle concerning [1,*n*] sigmatropic rearrangements of carbon outlined in the Introduction to this paper.

(4) There is a preference for retention of configuration at the migrating carbon in the bicyclo[6.1.0]nonatriene-to-bicyclo[4.2.1]nonatriene rearrangement. This derives not from a significant barrier to internal rotation but from the fact that the internal rotation that would be expected to lead to inversion instead returns the system to the lower-energy ring-walk manifold on the PES. The principal stereoisomer of the bicyclo[4.2.1]nonatriene product arises from a 1,3 migration with retention. The minor stereoisomer comes not from a 1,3 migration with inversion but rather from a 1,5 migration with retention.

(5) The preference for the 1,3 migration with retention in the bicyclo[6.1.0]nonatriene-to-bicyclo[4.2.1]nonatriene rearrangement is probably of dynamic origin. The stereochemistry is initiated during the initial bond-breaking event, which has to occur with the particular sense of internal rotation that will avoid the ring-walk reaction. This torsion defines the first product-forming transition structure to be encountered as that corresponding to a 1,3 migration with retention. The dependence of the product ratio on the sequence of encounter of the product-forming transition states is incompatible with a statistical kinetic model for the reaction.

(6) Stabilization of singlet biradicals by nitrile substituents may well facilitate the formation of such species, but the stabilization does not necessarily mean that the biradical will sit in a deeper minimum on the PES than its unsubstituted analogue would. In the two cases examined here, the nitrile substitution causes a reduction in the endothermicity of formation of the biradical by several kilocalories per mole but reduces the kinetic barrier by an essentially identical amount, thereby leaving the intermediate in a potential energy well just about as shallow as that for the parent hydrocarbon.

Acknowledgment. We thank the National Science Foundation (Grant No. CHE-9876387) for support of this research.

Supporting Information Available: Cartesian coordinates and energies of all stationary points from the calculations (PDF); X-ray crystal structure data for compounds **2** and **6** (CIF). This material is available free of charge via the Internet at http://pubs.acs.org.

JA017083J