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A Theoretical Comparison of Two Competing Diradical Cyclizations in Enyne-Allenes: The Myers−Saito and the Novel C^2-C^6 Cyclization

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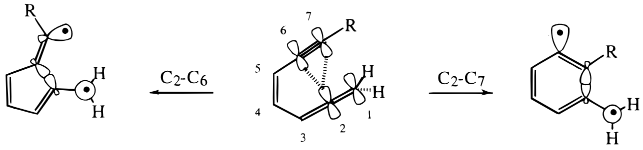
Abstract: The reaction mechanism and the energetics of the C^2-C^7 and of the C^2-C^6 cyclization of (*Z*)-1,2,4-heptatriene-6-yne are studied employing large scale MR-CI calculations. In addition the influence of vibrational motions and of temperature corrections on the barrier height of both reactions is estimated. For both products the first excited electronic states are computed to estimate possible switches from diradical to zwitterionic reaction mechanism.

1. Introduction

Since their first description[1,2] thermal C^2-C^7 cyclizations of enyne-allene compounds (Myers−Saito reaction) have been extensively investigated, because they possess a potential use as anticancer drugs and give the possibility to build up polycyclic ring systems. As indicated in Scheme 1 (right hand side) the first step of the Myers−Saito cyclization is the formation of a (σ,π)-diradical. Using the nomenclature of Salem and Rowland[3] such diradicals are called heterosymmetric diradicals. In spite of the use of different triggering modes such as light,[4] acid,[5] or base,[6] only Myers−Saito analogous products have been reported.

Recently, Schmittel and co-workers showed a remarkable switch from the well-known Myers−Saito C^2-C^7 cyclization to an uprecedented C^2-C^6 cyclization (left hand side of Scheme 1).[7−9] The switch from the Myers−Saito cyclization to the C^2-C^6 cyclization was triggered by replacing the hydrogen at the acetylene terminus (R = H) by an aryl group (R = Ph) or sterically bulky groups (R = tBu, $SiMe_3$). Using different substituents Gillmann[10] and Rodriguez[11] also found the new C^2-C^6 cyclization. Subsequent mechanistic[12] and DNA-cleaving[13] studies suggested that in analogy to the Myers−Saito reaction the new C^2-C^6 cyclization also proceeds via a diradical intermediate, but the final proof for this reaction mechanism is missing.

Scheme 1



The novel C^2-C^6 cyclization has intriguing potential for the construction of carbo- and heterocyclic ring systems.[9] In this work we present a comparison between the reaction mechanism of the Myers−Saito and the new C^2-C^6 cyclization using the (*Z*)-1,2,4-heptatriene-6-yne (R = H) as a model system. While no theoretical study of the C^2-C^6 cyclization is known, the Myers−Saito reaction was already studied by Koga and Morokuma,[14] who compard the Myers−Saito reaction with the Bergman reaction (C^1-C^6 cyclization of enediyne). In agreement with experimental results their computations find that the Myers−Saito reaction is more exothermic and requires a lower activation energy. Despite this agreement, the reaction energies computed for both reactions differ from other results, e.g., their prediction for the Bergman reaction deviates more than 15 kcal/mol from more recent computations employing the CASPT2 method[15] as well as from experimental results.[16] A similar difference exists between their prediction for the reaction energy of the Myers−Saito reaction (−0.7 kcal/mol) and an experimental estimate (−15 kcal/mol)[1] based on the group additivity assumption.[17] To resolve this discrepancy the Myers−Saito reaction is recalculated in the present work. Beside the energetics of both reactions also the influence of vibrational motions and of temperature corrections to the barrier height of both reactions are computed.

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(1) Myers, A. G.; Kuo, E. Y.; Finney, N. S. *J. Am. Chem. Soc*. **1989**, *111*, 8057.

(2) Nagata, R.; Yamanaka, H.; Okazaki, E.; Saito, I. *Tetrahedron Lett*. **1989**, *30*, 4995.

(3) Salem, L.; Rowland, C. *Angew. Chem*. **1972**, *84*, 86.

(4) Nakatani, K.; Isoe, S.; Maekawa, S.; Saito, I. *Tetrahedron Lett*. **1994**, *35*, 605.

(5) Scheuplein, S. W.; Machinek, R.; Suffert, J.; Brückner, R. *Tetrahedron ett*. **1994**, *34*, 6549.

(6) Toshima, K.; Ohta, K.; Ohtake, T.; Tatsuta, K. *Tetrahedron Lett*. **1991**, *32*, 391.

(7) Schmittel, M.; Strittmatter, M.; Kiau, S. *Tetrahedron Lett*. **1995**, *36*, 4975.

(8) Schmittel, M.; Kiau, S. *Liebigs Ann*. **1997**, 733.

(9) Schmittel, M.; Keller, M.; Kiau, S.; Strittmatter, M. *Chem. Eur. J*. **1997**, *3*, 807.

(10) Gillmann, T.; Hülsen, T.; Massa, W.; Wocadlo, S. *Synlett* **1995**, 1257.

(11) Garcia, J. G.; Ramos, B.; Pratt, L. M.; Rodriguez, A. *Tetrahedron Lett*. **1995**, *36*, 7391.

(12) Schmittel, M.; Strittmatter, M.; Kiau, S. *Angew. Chem*. **1996**, *108*, 1952.

(13) Schmittel, M.; Maywald, M.; Strittmatter, M. *Synlett* **1997**, 165.

(14) Koga, N.; Morokuma, K. *J. Am. Chem. Soc*. **1991**, *113*, 1907.

(15) Lindh, R.; Lee, T. J.; Bernhardsson, A.; Persson, B. J.; Karlström, G. *J. Am. Chem. Soc*. **1995**, *117*, 7186.

(16) Roth, W. R.; Hopf, H.; Horn, C. *Chem. Ber*. **1994**, *127*, 1765.

(17) Benson, S. W. *Thermochemical Kinetics*, 2nd ed.; Wiley: New York, 1976.

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Biradicals very often have low lying excited states with zwitterionic character. Donor−acceptor substitution patterns could stabilize the zwitterionic state so that they fall below the diradical state. In such a case the substituent induces a switch from a diradical to a zwitterionic mechanism. The vertical excitation energies of the low lying electronic states of both products are computed.

The Multi-Reference Configuration Interaction method in combination with an estimate of the unlinked cluster terms (MR-CI+Q) is used in the present study. Because the systems under consideration can become quite large due to the size of the substituents, less elaborated methods would be advantageous for a study of the substituent effects. Therefore, in the present study the semiempirical AM1 method[18] and density functional approaches are tested.

2. Computational Details

The C^2-C^7 and the C^2-C^6 cyclization are processes which involve the formal transformation of one doubly occupied π orbitals of the yne group and one doubly occupied π orbital of the terminal allene double bond to one doubly occupied σ bond and two singlet coupled singly occupied orbitals (p_σ and p_π) in both products (Scheme 1).

A correct description of such diradicals needs a Multi-Reference ansatz.[19,20] Therefore the geometries of both transition states (TS) of both diradical intermediates and of the reactant were optimized in the space of all $3N-6$ degrees of freedom of the system employing the complete active space SCF (CASSCF) method.[21] Information about the shape of the potential surface around the TS were obtained by computing the energy for fixed C^2-C^7 and C^2-C^6 distances which represent the reaction coordinates for the C^2-C^7 [14] and C^2-C^6 cyclization, respectively. In these calculations all other geometrical parameters were optimized. No symmetry constraints were used within the geometrical optimization, i.e., all optimizations were performed in C_1 symmetry. The structural labeling of the reactant, both transition states and both products, can be taken from Figure 1.

The active space of the CASSCF calculations included the π orbitals of the reactant, which in the course of the reaction form the π orbitals of the products, the orbitals which represent the bond formation and the singly occupied orbitals. This totals up to ten electrons in ten orbitals. These calculations will be denoted as CASSCF(10,10) computations. All CASSCF(10,10) calculations were performed with the MOLCAS[22] or the MOLPRO program package.[23]

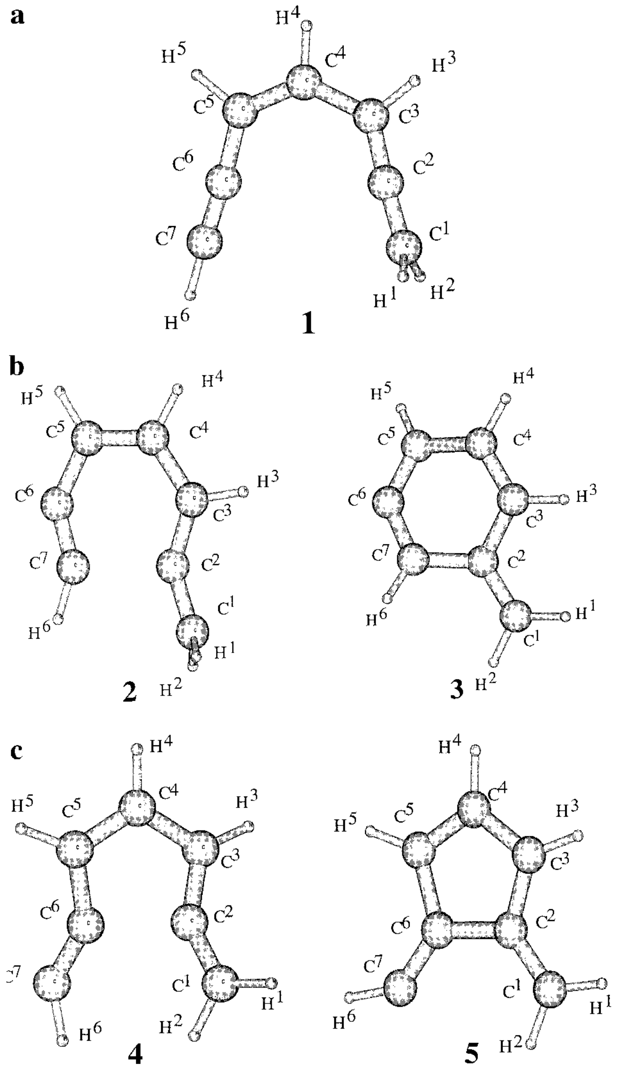

Figure 1. Structural labeling: (a) (*Z*)-1,2,4-heptatriene-6-yne (reactant) (**1**), (b) TS (**2**) and product (**3**) of the C^2-C^7 cyclization, and (c) TS (**4**) and product (**5**) of the C^2-C^6 cyclization.

For a quantitative description of such reactions dynamical electron correlation has also to be taken into account. In the present work these effects are included via an individually selecting MR-CI approach.[24] The reference space consists of up to 11 configurations leading to total MR-CI configuration spaces of more than 20 million configuration state functions (CSFs), whereby the secular equations actually solved were in the order of 2 million CSFs. The influence of the neglected CSFs is estimated via the Buenker−Peyerimhoff extrapolation scheme.[25] The influence of higher excitations are estimated by the normalized form of the usual Davidson correction.[26] In these calculations, in the following abbreviated as MR-CI+Q all 34 valence electrons were correlated. The calculations were performed with the DIESEL-MR-CI program package.[27] CASSCF(10,10) optimized geometries were used for the subsequent MR-CI+Q single point calculations. The MOs used for the MR-CI+Q calculations were also obtained from the CASSCF(10,10) computations. Because the use of less elaborated methods would be desirable for the study of substituent effects the density functions theory (DFT) and the semiempirical AM1 method were tested. Spin contamination effects can lead to large errors,[28] but the question arises whether both transition states

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(18) Dewar, M. J. S.; Zoebisch, E. G.; Healy, E. F.; Stewart, J. J. P. *J. Am. Chem. Soc.* **1985**, *107*, 3902.

(19) Klessinger, M.; Michl, J. In *Excited states and photochemistry of organic molecules*; VCH Publishers, Inc.: Weinheim, 1994.

(20) Szabo, A.; Ostlund, N. S. *Modern Quantum Chemistry*; Macmillan Publishing Co., Inc.: New York, 1982.

(21) Roos, B. O. *Int. J. Quantum Chem. Symp.* **1980**, *14*, 175.

(22) Andersson, K.; Fülscher, M. P.; Lindh, R.; Malmqvist, P.-A.; Olsen, J.; Roos, B. O.; Sadlej, A. J. MOLCAS Version 2; University of Lund: Sweden, P.O. Widmark, IBM Sweden, 1991.

(23) MOLPRO is a package of ab initio programs written by Werner, H.-J.; and Knowles, P. J., with contributions from Almöf, J.; Amos, R. D.; Deegan, M. J. O.; Elbert, S. T.; Hampel, C.; Meyer, W.; Peterson, K.; Pitzer, R.; Stone, A. J.; Taylor, P. R.

(24) Hanrath, M.; Engels, B. *Chem. Phys.* **1997**, *225*, 197.

(25) Buenker, R. J.; Peyerimhoff, S. D. *Theor. Chim. Acta* **1975**, *39*, 217. Buenker, S. D.; Peyerimhoff, S. D.; Butscher, W. *Mol. Phys.* **1978**, *35*, 771. Buenker, R. J.; Phillips, R. A. *J. Mol. Struct. THEOCHEM* **1985**, *123*, 291 and references therein.

(26) Del Bene, J. E.; Stahlberg, E. A.; Shaviatt, I. *Int. J. Quantum. Chem. Symp.*

(27) Engels, B.; Hanrath, M.: DIESEL-MR-CI (Direct Internal external separated individually selecting MR-CI) program package; University of Bonn: Germany, 1997.

(28) Baker, J.; Muir, M.; Andzelm, J. *J. Chem. Phys.* **1995**, *102*, 2063.

Table 1. Summary of the Energetical Data[a]

	structure			
reactant[b]	CASSCF(10,10)	MR-CI+Q	AM1	DFT
	−268.577619	−269.327852	114.2[c]	−270.201689
	C^2-C^7 Cyclization			
$R_{C^2-C^7} = 2.2$	25	24	21	21
$R_{C^2-C^7} = 2.07$[d]	29	25	27	22
$R_{C^2-C^7} = 2.0$	31	24	36[e]	21
$R_{C^2-C^7} = 1.43$[f]	4	−21	−5	−17
	C^2-C^6 Cyclization			
$R_{C^2-C^6} = 2.0$	35	27	38	30
$R_{C^2-C^6} = 1.9$[g]	37	35	44	31
$R_{C^2-C^6} = 1.8$	31	30	42	21
$R_{C^2-C^6} = 1.51$[h]	18	12	20	9

[a] While the energies of the reactant are given in hartree, the energies computed for the other structures are given relative to the reactant. These values are given in kcal/mol. Distances are given in Å. [b] Educt (structure **1**, see Figure 1a). [c] Reaction enthalpy (in kcal/mol). [d] TS of the C^2-C^7 cyclization (structure **2**, see Figure 1b). [e] The AM1 method finds the barrier at $R_{C^1-C^7} = 1.9$ Å. The barrier height is 38 kcal/mol. [f] Product of the C^2-C^7 cyclization (structure **3**, see Figure 1b). [g] TS of the C^2-C^6 cyclization (structure **4**, see Figure 1c). [h] Product of the C^2-C^6 cyclization (structure **5**, see Figure 1c).

which are important for the description of the switch from the C^2-C^7 cyclization to the C^2-C^6 cyclization, already possess diradical character. Consequently, it could be that DFT fails to predict a quantitative value for the stabilization energy but is able to describe the activation energies of both processes. Furthermore, in some instances DFT seems to be able to give a reliable description of diradical reactions.[29] For the DFT computations of the present work the Gaussian94 program[30] was employed. All calculations were performed with Becke's three parameter functional[31] where the nonlocal correlation is provided by the Lee−Yang−Parr expression[32] (B3LYP).

The AM1 calculations were performed with the MOPAC 6.0 program package.[33] Within the calculation a small CI calculation was employed.

In the present DFT calculations the 6-31G* basis set was employed. For the MR-CI calculations we used the standard Huzinaga (9s5p) AO basis set in the Dunning [4s2p] contraction[34] for carbon. A d-function with exponent of 0.7 was added. For the hydrogen the [2s] Dunning contraction of the standard Huzinaga (4s) AO basis was employed.[34] For the Bergman reaction[15] it was found that the computed barrier height increases by about 1−2 kcal/mol if larger basis sets are employed. Employing a basis of triple-ζ quality with two d functions we found similar dependencies for the Myers−Saito cyclization and the C^2-C^6 cyclization.

3. Results and Discussion

The results of the present work are summarized in Tables 1 and 2. Table 1 contains the energetics of both reactions. The geometrical parameters obtained for the reactant, both transition states (TS), and both products are given in Table 2. The structural labeling of the various optimized geometries can be taken from Figure 1. We will first concentrate on the MR-CI+Q//CASSCF(10,10) results. At the CASSCF(10,10) level the barrier for the C^2-C^7 cyclization is found for $R_{C^2-C^7} \approx 1.98$ Å. Including dynamic correlation effects via the MR-CI+Q method the barrier is shifted to $R_{C^2-C^7} = 2.07$ Å, and a barrier height of 25 kcal/mol is predicted. From investigation of the Bergman reaction[15] we expect that the barrier height raises to about 27 kcal/mol if better AO basis sets are employed. Experiments performed on the Myers−Saito reaction of which was obtained for 1-*n*-butyl-3-[2-(1-ethynyl)phenyl]-1,2-propadienyl(diphenyl) phosphine oxide give a barrier height of 21−23 kcal/mol.[7−9] In difference to the model system used in the present work [(*Z*)-1,2,4-heptatriene-6-yne] it possesses a $-POPh_2$ attached to the allenic group. Additionally, the C^5-C^4 double bond is replaced by a benzene ring. Test calculations show that the $-POPh_2$ group reduces the barrier height by about 3 kcal/mol.[35] Considering the influences of the additional groups both theory and experiment show a good agreement.

At the MR-CI+Q level the reaction energy ($E_{reactant} - E_{product}$) of the Myers−Saito reaction is −21 kcal/mol.[36] Computations employing an improved AO basis set[37] gave a reaction energy of −18 kcal/mol. This value agrees with the estimate given by Myers and co-workers,[1] who obtained a value of −15 kcal/mol. The result of Myers and co-workers is based on the group additivity assumption.[17] The diradical character of the C^2-C^7 cyclization product is obvious from the wave function data in Table 3. The shape of the singly occupied orbitals is displayed in Figure 3.

Changes of the geometrical parameters along the C^2-C^7 cyclization computed in the present work are very similar to the values given by Koga and Morokuma.[14] The main deviation between both studies is the prediction of the position of the barrier (Koga and Morokuma: 1.961 Å; present work: 2.07 Å). The value of Koga and Morokuma agrees to our CASSCF(10,10) result. The inclusion of dynamical correlation effect (via the MR-CI+Q) leads to an elongation of $R_{C^2-C^7}$. Using a CASSCF(10,10) method we find that the methylene group is rotated around the C^1-C^2 axis by about 5°, i.e., the rotation of the methylene group takes place after the transition state is passed. At the transition state both the $C{=}CH_2$ bond (reactant: 1.32 Å, TS: 1.35 Å product: 1.41 Å) and the triple bond are only partially broken (reactant: 1.21 Å, TS: 1.26 Å product: 1.38 Å), i.e., all geometrical parameters show that the transition state resembles more the reactant than the product. This can also be seen from Table 3, which gives the change in the composition of the CASSCF(10,10) wave function along both reaction paths. Table 3 shows only small differences between the wave functions of the reactant and the transition state of the C^2-C^7 cyclization. The product **3** of the C^2-C^7 cyclization (See Figure 1b) possesses a planar C_6 ring with the methylene CH bonds lying in plane. This nuclear arrangement results from the conjugation between the aromatic and the methylene π orbitals.

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(29) Goldstein, E.; Beno, B.; Houk, K. N. *J. Am. Chem. Soc*. **1996**, *118*, 6036.

(30) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Gill, P. M. W.; Johnson, B. G.; Robb, M. A.; Cheeseman, J. R.; Keith, T.; Petersson, G. A.; Montgomery, J. A.; Raghavachari, K.; Al-Laham, M. A.; Zakrzewski, V. G.; Ortiz, J. V.; Foresman, J. B.; Peng, C. Y.; Ayala, P. Y.; Chen, W.; Wong, M. W.; Andres, J. L.; Replogle, E. S.; Gomperts, R.; Martin, R. L.; Fox, D. J.; Binkley, J. S.; Defrees, D. J.; Baker, J.; Stewart, J. P.; Head-Gordon, M.; Gonzalez, C.; Pople, J. A. *Gaussian 94, Revision B.3*; Gaussian, Inc.: Pittsburgh, PA, 1995.

(31) Becke, A. D. *J. Chem. Phys*. **1993**, *98*, 5648.

(32) Lee, C.; Yang, W.; Parr, R. G. *Phys. Rev. B* **1988**, *37*, 785.

(33) Stewart, J. J. P. *QCPE Bull*. **1985**, *5*, 133.

(34) Dunning, Jr., T. H. *J. Chem. Phys*. **1970**, *53*, 2823.

(35) Engels, B. Manuscript in preparation.

(36) As already discussed Koga and Morokuma[14] computed a reaction energy of −0.7 kcal/mol for the Myers−Saito reaction. The major differences between our approach and the method employed by Koga and Morokuma consists in the number of selected configurations which are handled variationally. Test calculations indicate that the selection thresholds used by Koga and Morokuma (10^{-5} hartree) are too large, i.e., the number of configurations handled variationally is too small to obtain accurate results.

(37) For carbon we used the (14s9p4d) → [5s3p1d] ANO basis set as proposed by Widmark et al.[38] For hydrogen the (8s4p) → [2s1p] basis set was used.[38]

Table 2. Summary of the Geometrical Parameter Optimized for the Reactant (**1**), Both Products (**3** and **5**), and Both Transition States (**2** and **4**)[a]

	1[b]		**2**[c]		**3**[d]		**4**[e]		**5**[f]	
parameter	DFT	CAS	DFT	CAS	DFT	CAS	DFT	CAS	DFT	CAS
Reaction Coordinates										
$R_{C^2-C^7}$	3.70	3.70	2.08	2.08[g]	1.44	1.43	2.78	2.83	2.53	2.54
$R_{C^2-C^6}$	3.16	3.14	2.66	2.69	2.40	2.41	1.90	1.90	1.51	1.51
Secondary Coordinates										
$R_{C^1-C^2}$	1.30	1.32	1.33	1.35	1.40	1.41	1.34	1.35	1.36	1.36
$R_{C^2-C^3}$	1.32	1.32	1.36	1.35	1.43	1.45	1.38	1.39	1.43	1.43
$R_{C^3-C^4}$	1.46	1.47	1.42	1.45	1.39	1.39	1.42	1.44	1.41	1.42
$R_{C^4-C^5}$	1.35	1.35	1.38	1.36	1.41	1.41	1.37	1.36	1.38	1.38
$R_{C^5-C^6}$	1.42	1.44	1.39	1.43	1.38	1.39	1.43	1.46	1.47	1.52
$R_{C^6-C^7}$	1.21	1.21	1.25	1.26	1.37	1.38	1.28	1.29	1.32	1.33
$R_{C^7-H^6}$	1.07	1.06	1.07	1.06	1.09	1.08	1.08	1.07	1.08	1.08
$\angle(C^1-C^2-C^3)$	176.4	174.5	144.3	144.5	121.6	121.2	143.4	137.5	128.1	127.7
$\angle(C^2-C^3-C^4)$	128.8	128.1	128.5	128.4	121.9	121.4	112.3	112.9	109.5	110.7
$\angle(C^3-C^4-C^5)$	129.9	129.7	123.2	123.7	120.7	120.7	112.9	113.6	110.5	110.3
$\angle(C^4-C^5-C^6)$	127.2	126.9	115.6	117.1	116.1	117.1	114.9	114.3	108.5	108.3
$\angle(C^5-C^6-C^7)$	175.9	175.3	141.4	138.1	126.3	125.2	143.0	138.5	127.3	128.0
$\angle(C^6-C^7-H^6)$	177.7	177.4	147.3	147.5	117.8	121.3	137.2	139.3	137.7	136.5
$\angle(C^7-C^2-C^3)$			107.6	107.3	117.1	117.1				
$\angle(C^6-C^2-C^3)$							99.7	99.8	105.7	105.6
$\angle(H^1-C^1-C^2-C^3)$	90.0	90.0	42.1	85.7	0.0	0.0	12.5	15.4	0.0	0.0
$\angle(C^1-C^2-C^3-C^4)$	180.0	180.0	−157.6	−173.0	180.0	180.0	143.7	157.1	180.0	180.0
$\angle(C^2-C^3-C^4-C^5)$	0.0	0.0	−10.0	−1.9	0.0	0.0	14.2	10.7	0.0	0.0
$\angle(C^3-C^4-C^5-C^6)$	0.0	0.0	10.0	1.4	0.0	0.0	1.0	0.6	0.0	0.0

[a] The numbering of the centers is explained in Figure 1. The abbreviation DFT indicates computations performed with the DFT/B3LYP method in combination with a 6-31G* basis set, while the abbreviation CAS is used for a geometry optimization performed with the CASSCF method correlating 10 electrons in 10 orbitals. For the CASSCF calculations 6-31G** AO basis sets were used. Distances are given in Å, angles in deg. For more information see text. [b] Reactant (Figure 1a). [c] TS of the C^2-C^7 cyclization (Figure 1b). [d] Product of the C^2-C^7 cyclization (Figure 1c). [e] TS of the C^2-C^6 cyclization (Figure 1d). [f] Product of the C^2-C^6 cyclization (Figure 1e). [g] A TS optimization employing CASSCF calculations gave an optimized distance of 2.00 Å. Dynamical correlation effects shifted the top of the barrier to 2.08 Å. Therefore for the reaction coordinate the more reliable MR-CI values are given. For more information see text and Table 1.

Table 3. Change in the Composition of the Electronic Wave Function Along Both Reaction Coordinates[h]

	structure			
	CASSCF			DFT
reactant[c]	$\lvert\ldots p_\pi^2\rvert$	$\lvert\ldots p_\pi^{*2}\rvert$[a]	$\lvert\ldots p_\sigma^1\, p_\pi^1\rvert$[b]	$\langle S^2\rangle$
	0.822	0.031	<0.003	0.0
C^2-C^7 Cyclization				
$R_{C^2-C^7} = 2.2$	0.789	0.003	<0.003	0.00
$R_{C^2-C^7} = 2.07$[d]	0.766	0.056	<0.003	0.00
$R_{C^2-C^7} = 2.0$	0.735	0.069	<0.003	0.00
$R_{C^2-C^7} = 1.43$[e]	<0.003	<0.003	0.812	1.05
C^2-C^6 Cyclization				
$R_{C^2-C^6} = 2.0$	0.769	0.038	<0.003	0.00
$R_{C^2-C^6} = 1.9$[f]	0.659	0.140	<0.003	0.00
$R_{C^2-C^6} = 1.8$	0.393	0.391	0.008	1.05
$R_{C^2-C^6} = 1.51$[g]	0.092	0.093	0.634	1.04

[a] p_π^* represents the first virtual orbital. [b] Represents the singlet linear combination of both possible determinants: $|\ldots p_\sigma^1\, p_\pi^1| \equiv 1/\sqrt{2}\{|\ldots \overline{p_\sigma}^1\, p_\pi^1| - |\ldots p_\sigma^1 \overline{p_\pi}^1|\}$. [c] Structure **1** (see Figure 1a). [d] TS of the C^2-C^7 cyclization (structure **2** Figure 1b). [e] Product of the C^2-C^7 cyclization (structure **3** Figure 1c). [f] TS of the C^2-C^6 cyclization (structure **4** Figure 1d). [g] Product of the C^2-C^6 cyclization (structure **5** Figure 1e). [h] For the CASSCF wave function of the relative weight of the closed shell configuration (reactant) and the open shell configuration (product) is given. For comparison the $\langle S^2\rangle$ expectation value of the DFT wave function is added. (Distances are given in Å). A sketch of the relevant orbitals can be taken from Figures 2−4.

For the C^2-C^6 cyclization the MR-CI+Q method predicts a barrier of 35 kcal/mol, i.e., for (*Z*)-1,2,4-heptatriene-6-yne the barrier of the C^2-C^6 cyclization is 10 kcal/mol higher than the barrier of the C^2-C^7 cyclization. This agrees with the experimental results which find only Myers−Saito products for (*Z*)-1,2,4-heptatriene-6-yne.[1,2] The MR-CI+Q method predicts the C^2-C^6 cyclization to be endothermic by about 12 kcal/mol. In difference to the C^2-C^7 cyclization, this value does not change if an improved basis set[37] is used. The product **5** of the C^2-C^6 cyclization is sketched in Figure 1c. The CASSCF(10,10) method leads to a planar fulvene structure with the methylenic CH bonds lying in plane. As shown in Table 3 the product of the C^2-C^6 cyclization is a diradical. While both the AM1 method and the CASSCF method agree in the overall geometrical structure, a considerable difference between the results of both methods exists in the $C^6-C^7-H^6$ angle. While AM1 gives a value of 180°, the more sophisticated CASSCF(10,10) method predicts a strongly bend structure with $\angle(C^6-C^7-H^6) = 137°$, i.e., while the AM1 method predicts a π-type radical character for C^7, the CASSCF(10,10) method shows that C^7 represents a σ-type radical center. At the CASSCF(10,10) level the isomer given in Figure 1c is more or less isoenergetic to the isomer where the C^7-H^6 bond points toward the methylene group. The singly occupied orbitals of the C^2-C^6 cyclization product are displayed in Figure 4.

For the C^2-C^6 cyclization the barrier is found for $R_{C^2-C^6} = 1.9$ Å. The transition structure **4** (Figure 1c) has a distorted geometry possessing C_1 symmetry. In contrast to the C^2-C^7 cyclization, the rotation of the methyl group has already taken place to a large extent ($\angle(H^1-C^1-C^2-C^3) = 157°$), showing that the conjugation between the π orbitals of the methylene group and the π system of the ring is large enough to compensate the loss of the π-bond between C^2 and C^1. From the carbon skeleton only the centers C^3-C^7 lie on one plane ($\angle C^3-C^4-C^5-C^6 = 1°$), while the $C{=}CH_2$ group is rotated around the C^3-C^4 bond ($\angle C^2-C^3-C^4-C^5 = 11°$) in a way that it lies above the plane spanned by the other carbon centers. For the transition state the bond distances $R_{C^1-C^2}$ (1.35 Å) and $R_{C^6-C^7}$ (1.29 Å) lie between the values of the reactant (1.30 and 1.21 Å, respectively) and the product (1.36 and 1.33 Å,

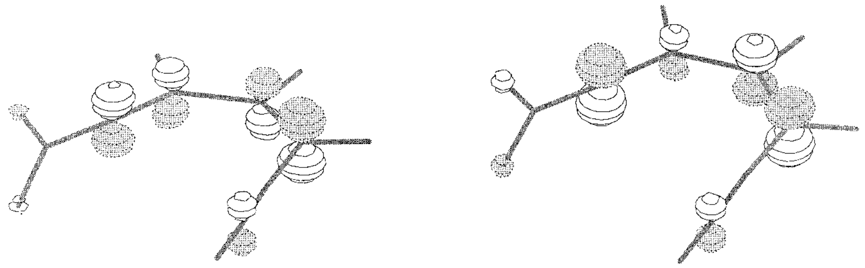

Figure 2. HOMO (left) and LUMO (right) of the reactant obtained from the DFT/6-31G* calculation.

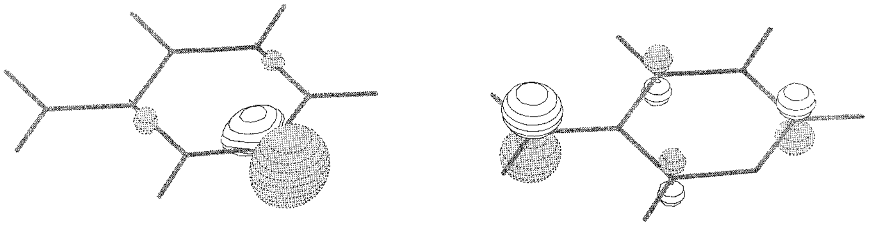

Figure 3. Singly occupied orbitals of the C^2-C^7 cyclization product (Myers−Saito cyclization) obtained from the DFT/6-31G* calculation.

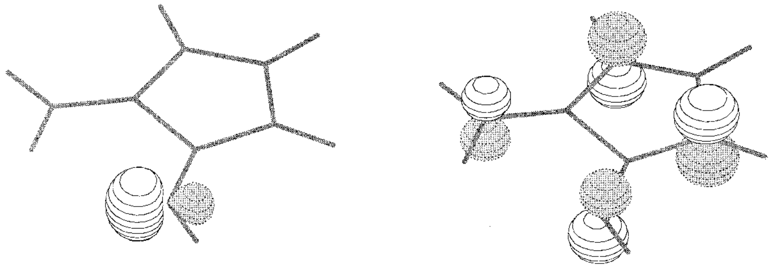

Figure 4. Singly occupied orbitals of the C^2-C^6 cyclization product obtained from the DFT/6-31G* calculation.

respectively). All geometrical parameters show that the transition state of the C^2-C^6 cyclization appears later than the transition state of the C^2-C^7 cyclization. This finding is supported by Table 3, which shows that at the transition state of the C^2-C^6 cyclization the electronic wave function starts to change. However, for $R_{C^2-C^6} = 1.9$ Å the wave function still resembles more the reactant than the product wave function. The strong change in the wave function happens between $R_{C^2-C^6} = 1.9$ and 1.8 Å.

Due to the size of possible substituents it would be desirable to study substituent effects with less sophisticated methods. Tables 1 and 2 show a comparison of the MR-CI+Q results with AM1 and DFT data. As shown in Table 1 the AM1 method is not suitable for the description of the energetics of both reactions. The method seems to describe the reactant better than the products. With respect to the reactant both products are found at too high energies, and the barrier heights of both reactions are strongly overestimated. Furthermore, for the C^2-C^7 cyclization the barrier is found at $R_{C^2-C^7} = 1.9$ Å, instead of 2.07 Å (MR-CI+Q).

The geometrical changes along both pathways are described qualitatively correct if DFT is employed (Table 2). This is also true for both products, where the DFT wave function possesses severe spin contamination. With respect to the CASSCF(10,10) method the DFT predicts a somewhat different geometry for the transition state of the C^2-C^7 cyclization. DFT gives a transition state geometry, which is more distorted out of the C_s symmetry, and the rotation of the methylene group has already taken place to a large extent ($\angle(H^1-C^1-C^2-C^3)$: 85.7°[CASSCF(10,10)] vs 42.1°[DFT]).

Density functional methods have been proven to give reasonable reaction barriers for a number a reactions,[28,39,40] but difficulties can arise if the DFT wave function suffers from strong spin contamination. However, in the present case DFT describes the reaction barriers and reaction energies reasonably (Table 1). Although the DFT wave functions show a mixing from the singlet and the triplet state ($S^2 \sim 1$) for the diradicals, the computed reaction energies deviate by only 3−4 kcal/mol from MR-CR+Q results. The reason for the accuracy of the DFT results could be the small energy gap between the singlet and the triplet state (Table 5). Larger deviations between the MR-CI+Q and the DFT results exist shortly after the reaction barrier, e.g., for $R_{C^2-C^6} = 1.8$ Å (+30 vs 21 kcal/mol).

Table 4. Influence of Vibrational and Temperature Corrections on the Reaction Barriers of Both Reactions[a]

	reactant[b]	TS1[c]	TS2[d]
ΔE_{zero}	66.1	66.0	65.1
S	85.7	77.1	77.9
$\Delta E^{\ddagger}$	−270.2017[e]	22	31
$\Delta H^{\ddagger}$ (298 K)	−270.0941[e]	21	29
$\Delta G^{\ddagger}$ (298 K)	−270.1348[e]	24	31

[a] The vibrational frequencies are based on the force constants computed at the DFT/6-31G* level of theory. The influence of the vibrational motion on the total energy (ΔE_{zero}), activation energy $\Delta E^{\ddagger}$, activation enthalpies ($\Delta H^{\ddagger}$), and activation free energies ($\Delta G^{\ddagger}$) are given in kcal/mol. The entropy S is given in cal/mol Kelvin. [b] Structure **1** (see Figure 1a). [c] TS of the C^2-C^7 cyclization (structure **2**, see Figure 1b). [d] TS of the C^2-C^6 cyclization (structure **4**, see Figure 1c). [e] Absolute value in hartree.

Because the DFT method was proven to be able to describe both reaction barriers, this method is employed to estimate the

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(38) Widmark, P. O.; Malmqvist, P. A.; Roos, B. O. *Theor. Chim. Acta* **1990**, *77*, 291.
(39) Durant, J. L. *Chem. Phys. Lett.* **1996**, *256*, 595.
(40) Jursic, B. S. *Chem. Phys. Lett.* **1996**, *256*, 603.

Table 5. Vertical Excitation Energies of the Lowest Electronic States of Both Products[a]

state	ΔE_{S_0} [eV]	$\Delta E_{\text{reactant}}$ [kcal/mol]	
		Structure **3**[b]	
$S_0(1^1A'')$	0.0	−21	$\|...p_\sigma^1\, p_\pi^1\|$
$T(1^3A')$	0.0	−21	$\|...p_\sigma^1\, p_\pi^1\|$
$S_1(1^1A')$	2.0	20	$\|...p_\sigma^2\|$
		Structure **5**[c]	
$S_0(1^1A'')$	0.0	12	$\|...p_\sigma^1\, p_\pi^1\|$
$T(1^3A')$	−0.2	7	$\|...p_\sigma^1\, p_\pi^1\|$
$S_1(1^1A')$	1.3	42	$\|...p_\sigma^2\|$

[a] The MR-CI+Q method is used throughout. The excitation energy is given with respect to the lowest singlet state S_0 (ΔE_{S_0}) and with respect to the reactant ($\Delta E_{\text{reactant}}$). The state-character in terms of the dominating configurations in the final wave function is also given. [b] Product of the C^2-C^7 cyclization. [c] Product of the C^2-C^6 cyclization.

influence of temperature corrections on both reaction barriers. For vibrational contributions the harmonic oscillator approach was employed. Table 4 shows that temperature effects change both barriers only slightly. Comparing the activation free energies ($\Delta G^\ddagger$) a barrier of 24 kcal/mol is obtained for the C^2-C^7 cyclization, while for the C^2-C^6 cyclization 31 kcal/mol are computed. Consequently, such effects seem to be negligible, if the barrier heights are studied as a function of the various substituents.

Showing that the ground states of both products possess diradical character our calculations support a diradical mechanism for both reactions. However, due to a donor−acceptor interaction, substituents could stabilize excited electronic states possessing zwitterionic character. A general discussion of such effects can be taken from the literature.[3,42,43] To estimate the importance of such states for the mechanism of both reactions, the vertical excitation energies of the lowest electronically excited states of both products were computed. The results are summarized in Table 5. As expected,[19] singlet and triplet states arising from the $p_\sigma^1\, p_\pi^1$ occupation pattern (see Figures 3 and 4 for a plot of singly occupied orbitals) lie very close in energy (structure **3**: 0 kcal/mol; structure **5**: 5 kcal/mol). For **3** our results agree with previous investigations of the singlet−triplet gap by Wenthold et al.[44] Using a MCSCF(8,8) approach they obtained 3.02 kcal/mol, while a value of 0.31 kcal/mol was computed on the CISD+Q level of theory. Both values show that the inclusion of dynamical correlation effects diminish the singlet−triplet gap. This is in line with our MR-CI+Q results.

For both products the first excited singlet states have zwitterionic character, possessing doubly occupied p_σ orbitals. The verical excitation energies are 2.0 eV for the product of the C^2-C^7 cyclization, while 1.3 eV are obtained for the C^2-C^6 cyclization product. Our results are in line with the work of Salem and Rowland who expect a large energy difference between the zwitterionic and the diradical states for heterosymmetric diradicals. For both structures the first excited state lies much higher than the reactant (**3**: 20; **5**: 42 kcal/mol). This shows that a strong interaction with the substituent is necessary to stablize the zwitterionic state below the ground state, i.e., going from a diradical to a zwitterionic mechanism.

4. Summary

In the present study the reaction mechanisms and the energetics of the C^2-C^7 (Myers−Saito) reaction and of the C^2-C^6 cyclization of (*Z*)-1,2,4-heptatrien-6-yne are studied. Large scale MR-CI+Q computations predict a barrier height of 25 kcal/mol for the Myers−Saito reaction, while 35 kcal/mol are obtained for the C^2-C^6 cyclization. This agrees with the experimental results which find only Myers−Saito products for (*Z*)-1,2,4-heptatriene-6-yne.[1,2] The absolute value of the barrier height of the Myers−Saito reaction of (*Z*)-1,2,4-heptatriene-6-yne agrees with an experimental estimate (≈25 kcal/mol). At the MR-CI+Q level the reaction energy of the Myers−Saito reaction is −21 kcal/mol, while +12 kcal/mol are found for the C^2-C^6 cyclization. The geometrical parameters of C^2-C^7 cyclization transition states indicate that the reaction passes through a transition state possessing nearly C_s symmetry. The methylene rotation takes place after the transition state is passed. For the C^2-C^6 cyclization the rotation of the methyl group has already taken place to a large extent ($\angle(H^1-C^1-C^2-C^3 = 157°)$), showing that the conjugation between the π orbitals of the methylene group and the π system of the ring is large enough to compensate for the loss of the π-bond between C^2 and C^1. Vibrational motions and temperature effects are found to influence both reaction barriers only to a small extent.

As expected, the triplet states of both products are found to be nearly isoenergetic to the lowest lying singlet state. The first excited states have zwitterionic character which results from a doubly occupied p_σ orbitals. The vertical excitation energies are 2.0 eV (C^2-C^7 cyclization) and 1.3 eV (C^2-C^6 cyclization), respectively. This shows that strong interaction with a substituent is necessary to switch from a diradical to a zwitterionic mechanism.

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(41) For the C^2-C^7 cyclization DFT shows similar basis sets effects as the MR-CI+Q method. Using a 6-311G** AO basis the computed reaction energy decrease to about −12 kcal/mol.

(42) Bonacic-Koutecky, V.; Koutecky, J.; Michl, J. *Angew. Chem.* **1987**, *99*, 216.

(43) Kita, F.; Nau, W. M.; Adam, W.; Wirz, J. *J. Am. Chem. Soc.* **1995**, *117*, 8670.

(44) Wenthold, P. G.; Wierschke, S. G.; Nash, J. J.; Squires, R. R. *J. Am. Chem. Soc.* **1994**, *116*, 7378. Wenthold, P. G.; Wierschke, S. G.; Nash, J. J.; Squires, R. R. *J. Am. Chem. Soc.* **1993**, *115*, 12611.