

Identification of multiple transition structures on the potential energy hypersurface for [2+2] electrocyclization of the pentadienyl cation bearing a phosphorus in the 3-position

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Ab initio molecular orbital investigations of the [2+2] electrocyclization of 3-substituted pentadienyl cations, where the substituents are BH₂, AlH₂, OH, SH, NH₂, PH₂, or H, show significant substituent effects on the ground state conformations, transition structures, and energies of activation. Locating the transition structure for the cyclization of the PH₂-substituted system was particularly troublesome due to the tendency of the phosphorus group to undergo inversion. The AVS Chemistry Viewer, a data flow environment-based application for the analysis, visualization, and animation of molecular modeling results, proved useful in mapping the potential energy hypersurface and understanding the transition structures for this system.

Keywords: AVS, AVS Chemistry Viewer, Nazarov cyclization, electrocyclization, data flow

INTRODUCTION

The use of mathematical modeling and computational methods to simulate chemical structures, reactivity, properties, and activity has become an almost ubiquitous part of or-

ganic chemistry as it is practiced today. We have been using computational chemistry and quantum chemical visualization techniques¹ to explore the conformational potential energy hypersurface (PES) of the Lewis acid-catalyzed [2+2] electrocyclization reaction of 1,4-pentadien-3-ones known as the Nazarov cyclization.^{2,3a-c} Electrocyclization reactions generally involve the breaking or formation of a carbon-carbon bond simultaneously with the stereospecific rotation of a pair of methylene carbons. We have found that the energy of activation for the cyclization reaction, for example, is significantly lower when the β -silicon group rotates to the inside, rather than the outside, due to hyperconjugation in the transition state; β -methyl groups prefer the outer position due to torquoselectivity.^{3a} Visualization and real-time manipulation of the geometries and molecular orbitals using the AVS Chemistry Viewer (CV) were essential in this work. More recently, we have turned our attention to the potential design of novel reactions by altering the functional group at the 3-position of the pentadienyl cation to include both resonance-donating and -withdrawing groups (Figure 1).⁴ Problems associated with the location and identification of multiple transition structures on the PES when the substituent was phosphorus were expeditiously solved through the use of graphical representations and manipulations of the structures using the CV.

DATA FLOW ENVIRONMENT

The Application Visualization System, AVS, is an integrated graphical environment that allows the use of hard-

Color Plates for this article are on pages 301 and 302.

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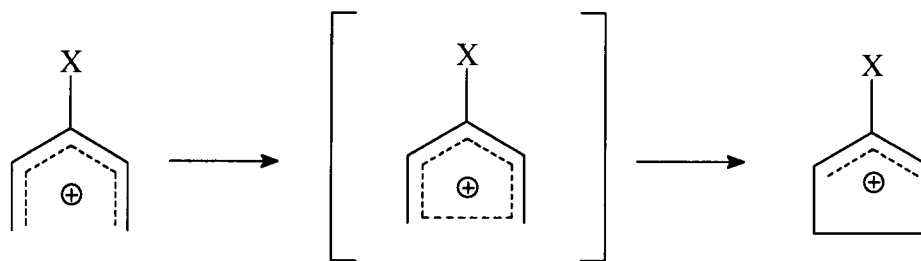


Figure 1. The 3-substituted $[2+2]$ electrocyclization reaction.

ware and software graphics capabilities to solve problems without requiring programming expertise.⁵ Users integrate modules of various types, which typically provide a single generalized functionality, into a visually constructed network or flowchart. Network connections specify the type and path of the data communicated between modules. Interactive applications are built using an upstream data paradigm that allows the output of one module to feed back into a preceding module as input. This functionality is most useful for screen picking and rotation–translation of an object on the screen. Execution of the network is controlled by the AVS flow executive, which controls the data flow through the network and schedules execution of a module when all of the requisite inputs are available or if any single parameter undergoes a change.

During its development, the architects of AVS created an externally defined, list-based molecule data type for the organization of molecules as atom-based, substructure, and quantum chemical information associated with a chemical species. This data type consists of 10 *CHEMobjects* composed of primitive data and pointers to other *CHEMobjects*.⁵ Despite this built-in functionality, almost no applications or modules developed by users take advantage of the molecule data type with the exception of the AVS Chemistry Viewer.¹ The Viewer provides primarily two types of functionality: (1) structure preparation and setup of a calculation, and (2) analysis of the optimized structure and molecular wavefunction output from various quantum chemical packages, including MOPAC and Gaussian 92. Interfaces to several other molecular modeling packages, including those for molecular mechanics and dynamics, allow preparation, analysis, and animation of molecular modeling results.

We used the CV to create our molecules and prepare the input deck for ab initio calculations using the Gaussian series of programs. This G9x_Setup network (Color Plate 1) allows the user to sketch and modify a molecule in three dimensions, set the hybridization of atoms (in order to provide a close approximation of the proper geometry), change atom types, set distances, bond and dihedral angles, and more. The molecule can be displayed as wireframe, ball and stick, stick, and spacefilling; all three visualization modes are available both during construction and analysis of the structure. Once the structures are prepared, a Z matrix can be built either automatically by the program or manually within the CV by the user. Autofill uses the atom numbering as defined during the molecular editing, which may not be optimal for the type of problem at hand. DefineZmatrix allows the user to select atom ordering in both the Z matrix and the structure by picking the atoms on screen with the

mouse. Finally, EditZmatrix allows the entries of the Z matrix to be typed in without exiting AVS.

After the structure has been drawn, cleaned up, and a Z matrix built, the G92 setup module is connected to the network. Selection of this module lets the user save the Z matrix in Gaussian 92 format, edit the command, job type and job title lines, and choose run options from menus. A short menu of options provides access only to energy procedures, basis sets, and types of runs, which are adequate for most uses. A full options menu allows access to all keyword options in Gaussian 92.

THEORETICAL METHODS

Ab initio calculations were carried out using the Gaussian series of programs⁶ on a Cray Y-MP/864. Structures were completely optimized starting from the previously obtained 1,4-pentadien-3-one cation geometries; no symmetry or other constraints were imposed. Restricted Hartree–Fock calculations leading to the stationary points were first performed using the 3-21G(*) split valence basis set,⁷ which contains *d*-type polarization functions on phosphorus, and were confirmed by frequency calculations. Second-order Moeller–Plesset electron correlation corrections⁸ were calculated as MP2/6-31G**//RHF/3-21G(*) single points, where the 6-31G** basis set includes *d*-type polarization functions on all nonhydrogen atoms and *p*-type polarization functions on hydrogens.⁹ Additionally, stationary points were located at the second-order Moeller–Plesset level of theory with the 6-31G* split valence basis set in order to compare optimizations performed both with and without correlation corrections.

RESULTS AND DISCUSSION

We examined the $[2+2]$ electrocyclization reaction for a series of 3-substituted pentadienyl cations, in which the substituent X in the 3-position was BH₂, AlH₂, OH, SH, NH₂, PH₂, or H, and observed significant substituent effects on the ground state conformations, transition structures, and energies of activation (Table 1).⁴ In all cases except for X = PH₂, location of the transition structure for the cyclization was straightforward. However, when X = PH₂ the initial transition structure located had a C1–C5 distance of 3.14 Å, nearly identical to the distance in the acyclic minimum energy conformation. Comparison to the C1–C5 distances in the other systems studied (cf. Table 2) made it obvious that this could not be the electrocyclization transition state.

Table 1. Activation energies for [2+2] electrocyclozation reaction of 3-substituted pentadienyl cations^a

	RHF/3-21G(*)	MP2/6-31G*
NH ₂	36.26	23.29
OH	30.67	15.94
SH	20.24	12.02
H	18.26	7.94
BH ₂	12.78	2.46
AlH ₂	11.77	1.48

^aDistances in angstroms.

Examination of the structure using the CV, in particular to visualize and animate using the vibrational analysis network (Color Plate 2), the negative eigenvalue associated with the transition structure revealed that this was the transition structure for the phosphorus inversion in the acyclic conformer (Color Plate 3). The visualization and animation clearly show the inversion process involving only the PH₂ group and C-3 of the chain.

We therefore set the C-1-C-5 distance to approximately 2.0 Å, using the upstream picking and molecular geometry editing capabilities of the CV, and allowed the system to optimize. This time, the resulting transition structure had a C-1-C-5 distance of 1.55 Å, nearly identical to the distance in the cyclic minimum and clearly too short to be the electrocyclozation transition state. Examination of the structure and negative vibrational frequency, as before, revealed that this was the transition structure for the phosphorus inversion in the cyclized system (Color Plate 4).

We solved the problem of locating the desired electrocyclozation transition structure by manually defining the Z matrix. Selecting atoms allowed us to fix specific atom relationships (i.e., by locking the two H-P-C-C angles at nonplanar values to avoid the inversion transition state by using the Z matrix editing capabilities of the CV). The molecule was optimized to locate a constrained cyclization transition state; subsequent removal of the constraints and complete optimization led to the desired electrocyclozation transition structure (Color Plate 5). The C-1-C-5 distance was 2.212 Å at the RHF/3-21G(*) level and 2.287 Å at the MP2/6-31G* level, in good agreement with the distances found for the transition structures with all other functional groups in the 3-position (Table 2). The PH₂ group is pyramidal and neither aligned with the mean plane formed by the five carbon atoms nor perpendicular to that plane, as

Table 2. Optimized C-1 to C-5 interatomic distance in the transition structure^a

	RHF/3-21G(*)	MP2/6-31G*
NH ₂	2.007	2.052
OH	2.087	2.140
SH	2.147	2.166
H	2.268	2.455
BH ₂	2.289	2.475
AlH ₂	2.284	2.541

^aDistances in angstroms.

was found in the previous two transition structures, respectively. The vibrational analysis clearly shows both the inward motion of the two carbons atoms and the concomitant disrotatory motion of the terminal methylene groups.

The MP2/6-31G**//RHF/3-21G(*) activation energies calculated for each of the three transition structures relative to the appropriate reference system is 6.29 kcal for the phosphorus inversion in the acyclic system, 36.26 kcal for the inversion in the cyclic system, and 5.10 kcal for the electrocyclozation. The extremely high value for the second inversion transition structure is primarily due to the lack of conjugation of the lone pair of electrons on phosphorus with the allyl-like cation in the five-membered ring, with some contribution from the rigidity and lack of permitted motion of the carbon atom bearing the phosphorus. Using the MP2/G-31G* optimized structures, the electrocyclozation faces a barrier of 5.92 kcal.

The geometric and energetic results let us quantify the conjugation of the phosphorus lone pair with the π system.¹⁰ The phosphorus inversion barrier in the cyclized product (36.26 kcal/mol) is the energy required for inversion when there is no conjugation, i.e., the phosphorus lone pair is orthogonal to the π system. The same barrier in the acyclic system (6.29 kcal/mol) is the energy required for inversion when there is maximum conjugation. The difference between the barrier heights, 29.19 kcal/mol, is the stabilization energy due to conjugation.

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